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THE PETROGENESIS AND TECTONIC SETTING OF THE NEW HAMPSHIRE PLUTONIC SUITE: TOWARDS A MORE COMPREHENSIVE MODEL FOR THE MAGMATISM OF THE ACADIAN OROGENY

MICHAEL J. DORAIS*,†

ABSTRACT. The Wamsutta and Nineteenmile Brook Diorites, two small plutons located in the White Mountains of New Hampshire, have bearing on the tectonic setting of magmatism between 410 and 407 Ma in this portion of the northern Appalachians. The unmetamorphosed, undated Nineteenmile Brook pluton has arc basalt affinities, produced in the same arc as the mafic magmas that were mingled with the ~410 Ma Meredeth Porphyric Granite of central New Hampshire. These volcanic arc magmas from a westerly dipping subduction zone contributed both heat and mass to the petrogenesis of the New Hampshire Plutonic Suite (NHPS), producing the high temperature melts of the Kinsman Granodiorite of the NHPS. These peraluminous NHPS magmas were emplaced during collision of Avalonia with Laurentia, forming the bases of Acadian thrust sheets. The ~408 Ma Wamsutta Diorite has appinite-like textures and chemically is a low SiO_2 adakite, with Sr/Y ratios of ~ 400 and $(La/Yb)_N$ between 80 and 130. These magmas were generated after flat slab, subduction erosion mixed basaltic rocks into the mantle wedge and partially melted the mafic rocks in the garnet stability field. The melts interacted with the surrounding peridotite to attain the low SiO_2 adakite characteristics. At this same time, the ~407 Ma Exeter Diorite and other arc plutons were emplaced in the Merrimack belt of southeastern New Hampshire. By 400 Ma, continued westerly dipping subduction provided mafic magma underplating to partially melt lower crustal amphibolites, generating the Spaulding Tonalite. Subsequently, lower crustal delamination and asthenospheric upwelling provided the heat source that produced a younger, post-tectonic suite of magmas between 390 and 370 Ma that, while having arc signatures because of the heritage of their crustal source rocks, are not arc magmas because subduction is thought to have ceased by this time. These plutons include the mafic rocks of the Northeast Kingdom of Vermont and the Mooselookmeguntic Igneous Complex of NH and ME. This same heat source may have contributed to melting lower to midcrustal metasediments to produce the widespread peraluminous Concord Granite of Vermont, New Hampshire, and western Maine.

Key words: Acadian Orogeny, subduction zone polarity, adakites, appinites

INTRODUCTION

New England consist of numerous terranes that were accreted to the Laurentian margin from multiple orogenic events ranging from the late Proterozoic Grenville Orogeny through a series of Paleozoic events culminating with the closure of Gondwana with Laurentia during the Alleghanian Orogeny at ~280 Ma. These Paleozoic orogenies include the ~470 Ma Taconic, the ~430 Ma Salinic, the ~410 Ma Acadian, the ~355 Ma Neoacadian, and the ~290 Ma Alleghanian, each with its own specific accreted terrane and tectonic history (Robinson and others, 1998; van Staal and others, 2009). Considerable debate regarding the polarity of Acadian subduction and prior to collision of the Avalonian microcontinent with amalgamated Laurentia has been presented in the literature (Bradley, 1983; Keppie and Dostal, 1994; Robinson and others, 1998; van Staal and others, 1998; Bradley and others, 2000; Eusden and others, 2000; Tucker and others, 2001; Bradley and Tucker, 2002; Schoonmaker and others, 2005, 2011; West and

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* Department of Geological Sciences, Brigham Young University, Provo, Utah 84602, USA
† Corresponding author: dorais@byu.edu

others, 2007; van Staal and others, 2009; Hibbard and others, 2010). Schoonmaker and others (2011) summarized the four scenarios that have been proposed to explain Acadian magmatism and tectonics: 1) slab detachment during southeast-directed subduction of the Laurentian continental margin; 2) Laramide-style thrust basins above a shallow, northwest-dipping subduction zone; 3) back-arc extension followed by thin-skinned shortening above a northwest-dipping subduction zone; and 4) Mollucan-style, dual-dipping subduction zones. The geochemistry of igneous rocks that were emplaced or erupted during the time frame of the Acadian Orogeny have the potential to clarify the polarity of Acadian subduction.

A belt of Silurian to early Devonian plutonic and volcanic rocks extends across New England and into Maritime Canada called the Piscataquis Volcanic Belt (fig. 1; Fyffe and others, 1981; Bradley, 1983; Osberg and others, 1985). The New Hampshire Plutonic Suite (NHPS, Billings, 1956; Dorais, 2003) of northern New England, a portion of the Piscataquis belt, consists of three syntectonic members, the Bethlehem Granodiorite, the Kinsman Granodiorite, and the Spaulding Tonalite (Billings, 1956), all intruded during the deformational events of the Acadian Orogeny between 413 and 400 Ma (Lyons and others, 1997), and the post-tectonic Concord Granite. Each of these members was emplaced along the bases of nappes and thrust sheets, being active participants in Acadian tectonism that was caused by the collision of Avalonia with the Laurentian margin.

The degree of deformation is strong in the Bethlehem Granodiorite (formally called the Bethlehem Gneiss; Billings, 1956) but is considerably less in the Kinsman Granodiorite (Dorais, 2003). The Spaulding Tonalite is rarely deformed; most of the fabric in the Spaulding is flow foliation. The Concord Granite, the post-tectonic member of the NHPS, was emplaced between 390 and 360 Ma. The source rocks, heat sources for melting, and the tectonic setting(s) that produced the NHPS have long been discussed (Lyons and Livingston, 1977; Clark and Lyons, 1986; Harrison and others, 1987; Hayward, 1989; Chamberlain and Sonder, 1990; Lathrop and others, 1994, 1996; Tomascak and others, 1996; Solar and others, 1998; Pressley and Brown, 1999; Dorais and Paige, 2000; Dorais, 2003; Dorais and others, 2009; Dorais and Tubrett, 2012; Dorais and Spencer, 2014; Dorais, 2019a).

The strongly peraluminous Bethlehem and Kinsman Granodioites requires a major metasedimentary component in the source rocks (Dorais, 2003). Despite the dominant sedimentary contribution to the magmas, the Kinsman Granodiorite contains mingled zones and enclaves with the mafic component preserving mantle isotopic signatures (Dorais, 2003). These mafic rocks, while not abundant, coupled with the high magmatic temperatures of the Kinsman Granodiorite (~800–850 °C; Dorais and others, 2009), require a heat source external to the thickened crustal section as crustal thickening processes alone do not to reach such high temperatures without mantle contributions in the form of heat and mass (Roselle and others, 2002; Lyubetskaya and Ague, 2010; Tassara and others, 2020). Additionally, the ~400 Ma metalumious Spaulding Tonalite is an I-type granitoid with inferred amphibolites as the source rocks (Dorais, 2003). Dehydration melting of amphibole requires temperatures in the 800 to 900 °C range (Wyllie and Wolf, 1993; Wolf and Wyllie, 1994), again requiring a mantle heat source.

Finally, the post-tectonic phase of the NHPS, the Concord Granite, is widespread across Vermont, New Hampshire, and western Maine (Dorais and Paige, 2000). Several models suggest that lower crustal materials partially melt 30 to 50 m.y. after crustal thickening because of the delay of high temperature isotherms sweeping upward through the colder, depressed fertile crust (England and Thompson, 1984; Chamberlain and England, 1985; Zen, 1988). But the presence of hornblende gabbros and quartz diorites in the 370 to 390 Ma Northeast Kingdom Batholith, in the

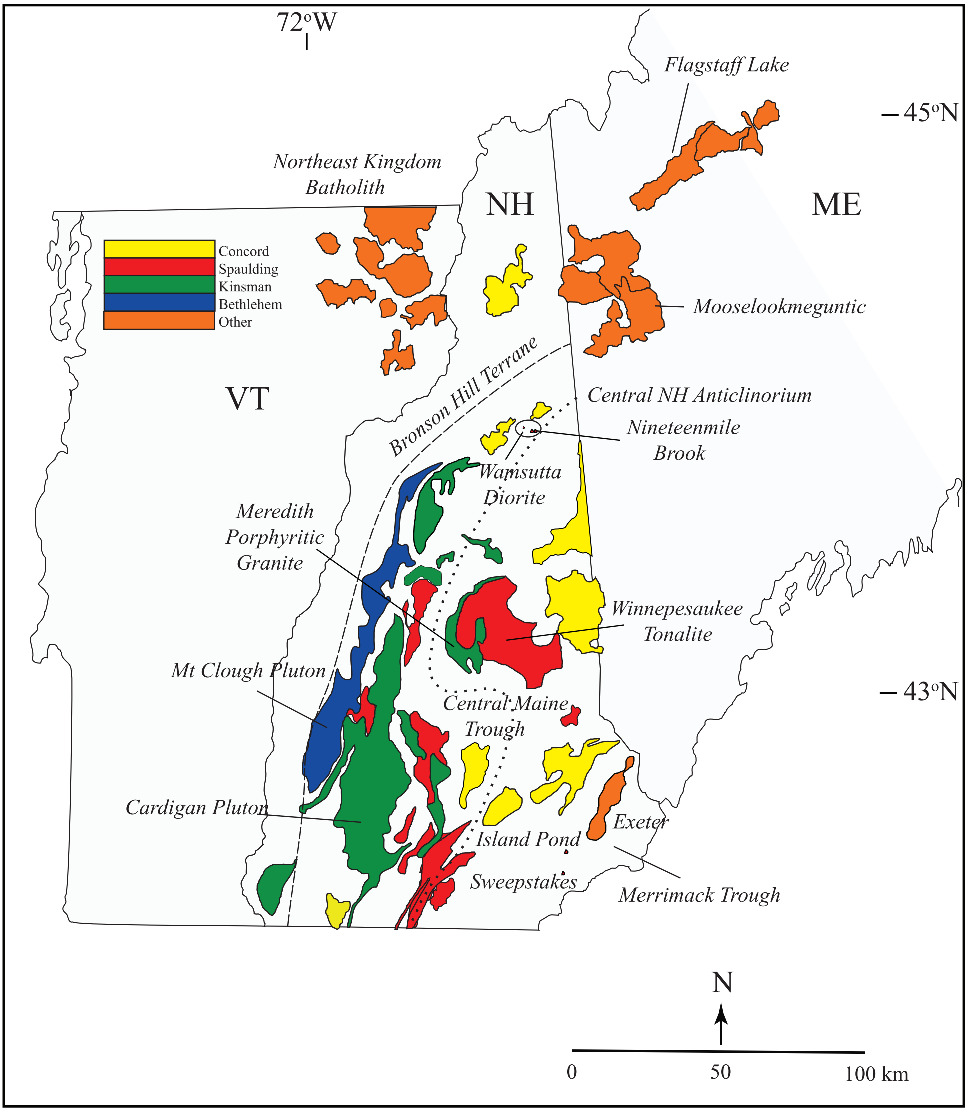

Fig. 1. Generalized geologic map of northern New England showing the locations of the Wamsutta and Nineteenmile Brook diorites, Flagstaff Lake Igneous Complex, Winnipesaukee Tonalite, Meredith Porphyritic Granite, Exeter Diorite, and Sweepstakes Diorite. The four members of the New Hampshire Plutonic Suite are color-coded. Plutons in Vermont, Maine and southeastern New Hampshire are not easily classified as NHPS members and are simply labeled as "other" plutons.

377±2 Ma Mooselookmeguntic Pluton of Maine (Tian, ms, 2000; Centorbi, ms, 2002), and the 383.8±2.2 Ma garnet tonalites of the Flagstaff Lake Igneous Complex of western Maine (Gibson and others, 2021; Nielsen and others, 1989) all indicate that the temperatures of anatexis from 390 to 370 Ma, at least in some portions of the orogeny, far exceeded that of muscovite dehydration melting (~700–750 °C; Vielzeuf and Holloway, 1988; Vielzeuf and Montel., 1994; Gardien and others, 1995) that occur during isotherm upsweep into thickened crust (England and Thompson, 1984). Additionally, the geochemistry of the mafic rocks of the Flagstaff Lake Igneous

Complex and other mafic rocks of the Piscataquis belt have long been problematic because some aspects of the chemistry are suggestive of arc magmas whereas others are more indicative of intraplate compositions (Hon and others, 1992; Schoonmaker and others, 2011). A more comprehensive model is needed to explain the variety of magma compositions that were emplace during and after the Acadian Orogeny from 413 to 370 Ma, and the distribution of these rocks across the terranes deformed by the Acadian Orogeny.

I sampled two mafic plutons in the Central Maine trough (fig. 1), the Wamsutta Diorite with an age of 408.4 Ma (Eusden and others, 2000), and the Nineteenmile Brook Diorite with an inferred age between 410 to 407 Ma (Billings and Fowler-Billings, 1975), in an attempt to determine the tectonic setting of these magmas and compare their compositions to previously published studies of plutons located across the Central Maine and Merrimack troughs. These data are combined with analyses of plutons of the Central Maine trough from previous studies, including the mingled, mafic rocks in the Meredith Porphyritc Granite of the ~410 Ma Kinsman Granodiorite, the ~400 Ma Spaulding Tonalite (Dorais, 2003; Dorais and others, 2009), and the ~400 Ma Flagstaff Lake Igneous Complex (Nielsen and others, 1989; Schoonmaker and others, 2011; Dorais and Campbell, 2022). The plutons of the Merrimack belt of southeastern New Hampshire are of this same age: these are the Exeter Diorite (407 Ma, Bothner and others, 2009), the Sweepstakes Diorite, and the Island Pond Diorite (fig. 1; Watts and others, 2000). Here I provide mineral and whole-rock analyses of the Wamsutta Diorite and the Nineteenmile Brook Pluton and compare these analyses with those of the Merrimack trough plutons and other mafic rocks of New Hampshire Plutonic Suite and attempt to synthesize all the data towards a more comprehensive model for the magmatism of the Acadian Orogeny.

GEOLOGIC SETTING AND PETROGRAPHY

Northern New England consists of several terranes that were accreted to the Laurentian margin through five Paleozoic orogenic events (Lyons and others, 1997; Ratcliffe and others, 2011). To the west, New England is underlain by rocks of Laurentian affinities; Mesoproterozoic to early Neoproterozoic basement rocks are exposed in the Green Mountains of Vermont. Eastward is an Ordovician arc and accretionary complex of the Shelburne Falls and Taconic arcs. Associated with these arcs and outboard of them is the Acadian orogenic hinterland that consists of Silurian to Devonian metasedimentary rocks of the Connecticut Valley-Gaspe, Central Maine, and the Merrimack troughs. Included in these tracts are the Bronson Hill anticlinorium of Silurian continental arc rocks and the peri-Gondwanan Massabesic Gneiss Complex (Dorais and others, 2012). Outward of these are the peri-Gondwanan terranes of the Nashoba belt (Hepburn and others, 1995) and the Merrimack trough (Hussey and others, 2010). Finally, extending from Boston, MA to Rhode Island and eastern Connecticut is peri-Gondwanan Avalonia (Nance and Thompson, 1996).

The Central Maine trough metasedimentary rocks of New Hampshire experienced multiple episodes of folding during the Acadian orogeny (Englund, 1976; Nielson, 1981; Lyons, 1988). F1 consists of east and west verging nappes that are separated by a pop up or dorsal zone (Eusden and others, 1987; Eusden and Lyons, 1993) called the Central New Hampshire anticlinorium with an axial trace extending north-northeast across central New Hampshire (fig. 1). The westward verging nappes subsequently experienced isoclinal to recumbent folding with northeast trending axes (F2). Broad open folds with northwest to westerly trending axes define F3. F4 is defined by open to isoclinal folds with northeast trending axes.

The Bethlehem Granodiorite is located in the western regions of the state and farthest from the dorsal zone. This member of the NHPS is the most tectonized of the three syntectonic members, traditionally having been called the Bethlehem Gneiss (Billings, 1956). The rock is a medium-grained biotite gneiss that is predominantly strongly to weakly foliated but in some locations, is unfoliated and massive. The dominant rock type in the Bethlehem is granodiorite, but granite is also abundant. Minor amounts of rocks as mafic as quartz diorite are also present. The Bethlehem consists of quartz, oligoclase-andesine, biotite, K-feldspar, and minor amounts of muscovite. Many grains are up to 5 millimeters in diameter, but these generally are aggregates of smaller grains from post-solidification deformation.

The Kinsman Granodiorite is located east of the Bethlehem plutons, closer to the dorsal zone. The largest Kinsman intrusion is the Cardigan pluton (fig. 1; Clark and Lyons, 1986; Dorais, 2003). There are several other large Kinsman-type plutons, including the Meredith Porphyritic Granite of the Winnipesaukee pluton (Quinn, 1944; Dorais, 2003). The Kinsman Granodiorite exhibits variable degrees of deformation but in general, not as much as the Bethlehem Granodiorite. It is a medium to coarse grained, massive to strongly foliated rock consisting of oligoclase-andesine, quartz, Kspar, biotite, muscovite and variable amounts of garnet. The rock is very distinctive with Kspar crystals up to 15 centimeters in length. The Kinsman is predominantly granodiorite, but a continuum exists between minor amounts of quartz diorite and relatively abundant granite. Some outcrops have garnetite pods consisting of up to 60 percent garnet (Clark and Lyons, 1986; Dorais and others, 2009, Dorais and Tubrett, 2012; Dorais and Spencer, 2014).

The Meredith Porphyritic Granite phase of the Kinsman Granodiorite is granodiorite to granite in composition, but minor amounts of more mafic rocks in the form of mafic enclaves and mingled zones are present, consisting primarily of tonalitic rocks (Dorais, 2003). These mafic rocks display typical quench and mingling features (Reid and others, 1983; Dorais and others, 1990).

Intermediate in age between the Kinsman Granodiorite and the Spaulding Tonalite is the Wamsutta Diorite (408.4 Ma, Eusden and others, 2000) and by inference the Nineteenmile Brook Diorite. The Wamsutta Diorite is located in the Great Gulf Wilderness of the Presidential Range and is exposed over less than a square kilometer (Eusden, 2010). This is the oldest pluton in the Presidential Range and has a weak S1 foliation that also cuts across the S1 fabric in the metasedimentary country rocks (Eusden and others, 2000). Eusden and others (2000) interpreted these observations to indicate that the Wamsutta Diorite intruded during the waning stages of F1 nappe-stage folding. The diorite thus represents the earliest syn-kinematic intrusion in the range and is probably in part synchronous with M1.

Comb layering is present in the pluton and acicular amphibole crystals with aspect ratios of 10:1 are common (fig. 2). The diorite contains ~40% subhedreal to anhedral amphibole grains that displays green to olive pleochroism, about 55% plagioclase, and about 5% pale brown biotite. Titanite is a common accessory phase along with minor zircon, apatite, and magnetite.

The Nineteenmile Brook Diorite along the stream of that same name in Pinkham Notch outcrops as two small oval bodies, one 0.6 km long and the other 0.2 km (Billings and Fowler-Billings, 1975). Billings and Fowler-Billings describe the dioritic pluton as being very heterogeneous in grain size, ranging from medium-coarse, medium-fine, and leucocratic fine grained, the latter occurring as small dikes that cut the coarser grained varieties. The average mode given by Billings and Fowler is 60% plagioclase, 32% amphibole that replaces orthopyroxene, 3% biotite, 5% magnetite with minor quartz.

The Spaulding comprises several moderately sized plutons located along a north south axis in the center of the state, primarily adjacent to the dorsal zone (fig. 1; Duke, ms, 1978). The largest of these is the 393±2 Ma Winnipesaukee Tonalite (fig.

Fig. 2. Photomicrograph of the Wamsutta Diorite showing elongated amphibole grains, plagioclase, and titanite. Field of view is 10 mm.

1) which, on the Geologic Map of New Hampshire, is listed as its own distinct plutonic member that is probably coeval with the Spaudling Tonalite (Lyons and others, 1997). Based on similar field relations, and mineralogic and geochemical characteristics (Dorais, 2003, 2019a), the Winnipesaukee Tonalite is part of the Spaulding Tonalite.

The Spaulding Tonalite is the most mafic of the NHPS. It ranges from quartz diorite to granite in composition (Quinn, 1944; Fowler-Billings, 1949; Duke, ms, 1978). The Winnipesaukee Tonalite covers this same compositional range and displays a distinct geographic variation in composition (Dorais, 2003). Quartz diorite is located along the western margin, tonalite in the central regions, and granodiorite to granite in the eastern portions of the pluton. In common with the other syntectonic members of the NHPS, the Winnipesaukee Tonalite exhibits variable degrees of deformation, but is less deformed than the Bethlehem and Kinsman, ranging from localized, moderately sheared rocks to undeformed rocks at many localities where deformation is not noted in outcrop or thin section. The nonfoliated, granitic portions of the pluton are similar to the post-tectonic Concord Granite.

The mineralogy of the Winnipesaukee Tonalite varies because the rocks span the range from metaluminous to peraluminous compositions. The more mafic portions of the Winnipesaukee Tonalite consist of minor amounts of quartz diorite with hornblende, plagioclase, and biotite as dominant minerals. Magmatic epidote is present in the hornblende-bearing rocks. With increasing silica content, hornblende proportions diminish, as biotite becomes the dominant mafic silicate. Muscovite is present in the most felsic rocks.

The Concord Granite (Lyons and others, 1997; Dorais and Paige, 2000) is a post-tectonic, two-mica granite named after the type pluton at Concord, New Hampshire (Hitchcock, 1877). The Concord Granite ranges from 30 to 50 Ma younger than the syntectonic NHPS plutons (Lyons and Livingston, 1977; Harrison and others, 1987; Lyons and others, 1997). Unlike the three syntectonic members of the NHPS, the Concord Granite shows no spatial pattern in emplacement, having intruded the CMT metasedimentary rocks across New Hampshire (fig. 1), in the Northeast Kingdom batholith of Vermont, and across western Maine.

Farther afield from the White Mountains are the Exeter Diorite of the Merrimack belt and the Flagstaff Lake Igneous Complex of western Maine. Nielsen and others (1989) describe the ~400 Ma Flagstaff Lake Igneous Complex as consisting of three main rock types: gabbro, granite, and garnet tonalite, with minor trondhjemite. Over 60 percent of the complex was mapped as gabbro that forms two separate bodies along the northeastern and southwestern portions of the complex (see fig. 1 of Nielsen and others, 1989). Schoonmaker and others (2011) demonstrated that the gabbroic portion of the complex ranges from gabbro to granite in composition with the dominant rock type being diorite. Most gabbros contain equal proportions of pyroxene and plagioclase with minor amphibole. The more abundant quartz diorites and tonalites consist of amphibole, biotite, plagioclase (An_{25-40}), variable amounts of quartz (10–25%) with magnetite, titanite, and apatite as the main accessory phases.

The Exeter, Sweepstakes, and Island Pond diorites are located in the Merrimack trough of southeastern New Hampshire (fig. 1; Watts and others, 2000). The Sweepstakes Pluton intrudes the Eliott Formation of the Merrimack Group (Sundeen 1971) and is the smallest Merrimack Trough pluton (~3.5 km^2) studied by Watts and others (2000). The most abundant rock type is massive to moderately flow-banded diorite and quartz diorite. Several small bodies of coarse-grained norite cumulates occur in the center of the body. Minerals present include biotite, plagioclase, and light brown, secondary amphibolite. Ilmenite is anhedral and commonly rimmed by titanite overgrowths. Anhedral quartz is a minor, interstitial phase.

Exposed approximately 6 kilometers to the north of the Sweepstakes Pluton, the Island Pond Pluton (-8 km^2) crops out as a northeast trending elliptical body (Sundeen, 1971). The pluton exhibits a bimodal range of rock compositions with two volumetrically subordinate bodies of coarse-grained, massive diorite in the core of the intrusion surrounded by massive to weakly foliated granitic rocks. The diorite contains normally zoned subhedral to anhedral plagioclase phenocrysts typically ranging from An_{30} to An_{25}. Pale to dark green amphibole is the dominant mafic silicate. Fe-Ti oxides are common along cleavage planes in hornblende. Lesser amounts of pale green to light yellow biotite are also present.

The largest pluton (~130 km^2) considered is the northeast trending Exeter Pluton. Dominantly dioritic in composition, the pluton is zoned from gabbro in the southwest to granodiorite at its northern end (Watts and others, 2000). The rocks are medium- to coarse-grained and massive in texture. Mafic rocks in the southern portion of the pluton generally retain much of their original igneous character whereas deuteric alteration is most pervasive in the northern portion of the pluton. The mafic rocks consist of hornblende, orthopyroxene ± clinopyroxene, biotite, plagioclase, and minor quartz. In some rocks, ortho- and clinopyroxene occur as anhedral remnants partially replaced by amphibole. In some portions of the pluton, light to dark brown amphibole phenocrysts partially enclose normally zoned plagioclase laths in a subophitic texture. Other regions contain rocks with pale green phenocrysts of hornblende that are commonly intergrown with biotite.

ANALYTICAL METHODS

Mineral analyses were conducted at Brigham Young University using a Cameca SX50 electron microprobe. Bulk-rock major and trace element XRF analyses were done with a Rigaku ZSX Primus II at BYU. Additional trace elements were determined by inductively coupled plasma mass spectrometry (ICP-MS) at ALS Chemex in Reno, Nevada. An evaluation of XRF, and ICP-MS precision and accuracy can be found in Supplementary1 table 1 of Dailey and others (2018).

RESULTS

Mineralogy

Amphibole.—Amphibole is present in both the Nineteenmile Brook and Wamsutta plutons (table 1). Figure 3A plots amphibole compositions of the two plutons and compares them with amphibole in the Merrimack belt plutons (Watts and others, 2000), the Flagstaff Lake Igneous Complex of Maine (Dorais and Campbell, 2022), and in the Sierra Nevada Batholith (Dodge and others, 1968; Dorais and others, 1990). The Wamsutta and Nineteenmile Brook plutons define a trend from ferro-tschermakite to actinolite. Most of the Wamsutta Pluton amphiboles plot at the Si-poor end of the trend as ferro-tschermakites though another cluster is magnesio-hornblende. The Merrimack belt plutons' amphiboles are dominantly magnesio-hornblende, plotting amongst the amphiboles of the Sierra Nevada Batholith and others from the Wamsutta Diorite. The Flagstaff Lake amphiboles are dominantly ferro-hornblende. The amphiboles from Nineteenmile Brook Diorite are magnesio-hornblende to actinolite.

In figure 3B, amphiboles in the Wamsutta, Nineteenmilebrook, Meredeth, and Sierra Nevada rocks define a negative trend from moderate to low alkali contents with decreasing Si, characterizing amphiboles in calc-alkaline rocks. At equivalent Si values, amphiboles from the alkaline rocks of the Jurassic to Cretaceous White Mountain Magma Series (Dorais, 1990; Dorais and Floss, 1992; Dorais and MacRae, 1994; Matos, ms, 2021) plot at higher alkali totals.

Biotite.—Figure 4 shows mica compositions for the Nineteenmile Brook and Wamsutta plutons (table 2) and for comparison, biotite compositions of the calc-alkaline Merrimack trough diorites, the Flagstaff Lake Igneous Complex, the Sierra Nevada Batholith (Dodge and others, 1969; Dorais and others, 1990). The A-type, Conway and Mount Osceola Granites (Matos, ms, 2021) and the Dry River Diorite of the Mesozoic White Mountain Batholith (Dorais, in prep) that were emplaced in the vicinity of the two studied plutons are also plotted. Biotite in the Nineteenmile Brook and Wamsutta is similar to that of the Merrimack trough diorites and the Sierra Nevada Batholith in Mg#, Al and Ti contents and have higher Mg/(Mg+Fe) values than the Flagstaff Lake biotite. They are slightly richer in Al and considerably poorer in Ti than biotite from the alkaline Dry River Diorite of the White Mountain Magma Series (WMMS). The Fe-rich composition of the WMMS A-type granites is evident compared to the more Mg-rich biotites of the Nineteenmile Brook and Wamsutta Diorites. Although the Nineteenmile Brook Diorite has not been dated, the similarity of its biotite and amphibole compositions with the calc-alkaline rocks of the Merrimack trough and the Sierra Nevada Batholith, and the differences in Nineteenmile Brook biotite compositions from that of the alkaline Conway, Mount Osceola, and Dry River Diorite of the WMMS, strongly suggest that the Nineteenmile Brook pluton has calc-alkaline affinities.

Feldspar.—Figure 5 plots plagioclase compositions (table 3) in the Wamsutta Diorite and the Nineteenmile Brook Pluton. Wamsutta Diorite plagioclase is more albitic, ranging from An_{3-29} whereas the plagioclase in the Ninteenmile Brook Diorite is considerably more anorthitic, ranging from An_{21-75}.

Whole-rock Compositions

The total alkali–silica diagram (fig. 6) shows that three of the four Wamsutta Diorite samples are richer in alkalis than samples of the Nineteenmile Brook, Flagstaff

Table 1

Representative amphibole analyses, Wamsutta Diorite and Nineteenmile Brook Pluton

	SiO_2	TiO_2	Al_2O_3	MgO	FeO	MnO	CaO	Na_2O	K_2O	F	Cl	Total	F=O	Cl=O	Total
WS-1-1	45.45	1.25	8.52	11.20	16.79	0.52	11.92	0.88	0.98	0.21	0.10	97.81	-0.09	-0.02	97.70
WS-1-2	46.18	1.08	8.05	11.63	16.69	0.48	11.96	0.91	0.91	0.15	0.08	98.13	-0.07	-0.02	98.05
WS-1-4	45.94	1.05	8.10	11.55	16.57	0.51	11.94	0.88	0.86	0.11	0.11	97.63	-0.05	-0.03	97.55
WS-1-5	45.90	1.10	8.21	11.54	16.42	0.45	11.95	0.90	0.93	0.17	0.11	97.68	-0.07	-0.03	97.58
WS-1-6	46.46	1.08	7.69	11.92	15.85	0.45	11.88	0.82	0.86	0.15	0.10	97.24	-0.06	-0.02	97.16
WS-1-7	46.41	1.12	7.85	11.86	16.08	0.58	11.91	0.85	0.92	0.15	0.14	97.87	-0.06	-0.03	97.77
WS-1-9	46.47	1.16	7.73	11.83	16.32	0.45	11.88	0.86	0.89	0.14	0.15	97.86	-0.06	-0.04	97.77
WS-1-10	46.59	1.11	7.89	11.83	16.04	0.44	11.97	0.87	0.88	0.20	0.15	97.97	-0.09	-0.04	97.85
WS-1-11	46.38	1.13	7.73	11.60	16.39	0.57	11.87	0.94	0.90	0.18	0.19	97.87	-0.07	-0.04	97.75
WS-1-12	46.02	1.12	7.82	11.57	16.33	0.55	11.84	0.97	0.91	0.18	0.18	97.49	-0.07	-0.04	97.37
WS-1-13	46.16	1.12	7.79	11.72	15.96	0.55	11.89	0.96	0.90	0.14	0.21	97.38	-0.06	-0.05	97.27
WS-1-14	46.30	1.13	7.69	11.45	16.23	0.50	11.87	0.89	0.89	0.19	0.20	97.34	-0.08	-0.04	97.22
WS-1-15	46.38	1.12	7.85	11.68	16.65	0.49	11.92	0.92	0.88	0.16	0.19	98.24	-0.07	-0.04	98.13
WS-1-17	46.50	1.14	7.79	11.83	16.20	0.47	11.92	0.87	0.90	0.21	0.15	97.97	-0.09	-0.03	97.85
WS-1-19	46.30	1.13	7.79	11.83	16.12	0.48	12.00	0.87	0.89	0.17	0.15	97.73	-0.07	-0.03	97.63
WS-1-20	46.80	1.04	7.52	12.10	15.92	0.48	12.00	0.84	0.85	0.18	0.18	97.92	-0.08	-0.04	97.80
WS-1-21	46.50	1.09	7.80	11.93	16.25	0.43	11.91	0.80	0.88	0.18	0.11	97.88	-0.07	-0.03	97.78
WS-1-23	46.22	1.07	8.09	11.69	16.51	0.46	11.96	0.86	0.87	0.16	0.11	98.00	-0.07	-0.02	97.91
WS-1-24	45.74	1.09	8.37	11.45	16.66	0.42	11.84	0.98	0.83	0.17	0.11	97.68	-0.07	-0.03	97.58
WS-2-2	40.91	0.57	10.76	9.28	20.49	0.21	12.14	1.52	1.22	0.56	0.02	97.66	-0.24	0.00	97.42
19-1-1a	51.65	0.08	4.68	15.58	11.68	0.22	12.72	0.63	0.49	0.81	0.00	98.53	-0.34	0.00	98.19
19-1-1b	51.08	0.10	5.36	15.23	11.71	0.25	12.69	0.72	0.62	0.85	0.00	98.60	-0.36	0.00	98.24
19-1-1d	52.09	0.08	4.31	15.78	11.40	0.17	12.70	0.62	0.55	0.87	0.01	98.57	-0.37	0.00	98.21
19-1-1e	53.87	0.04	2.79	16.56	10.79	0.23	12.83	0.42	0.28	0.81	0.00	98.60	-0.34	0.00	98.26
19-1-1f	51.70	0.09	5.09	15.34	11.55	0.18	12.56	0.71	0.59	0.89	0.01	98.72	-0.38	0.00	98.34
19-2-3a	51.56	0.28	6.79	15.82	11.16	0.26	11.67	0.60	0.09	0.16	0.00	98.39	-0.07	0.00	98.33
19-2-3b	51.82	0.39	6.05	16.35	10.99	0.23	11.86	0.55	0.10	0.10	0.00	98.44	-0.04	0.00	98.40
19-2-3f	51.51	0.26	5.86	16.08	11.71	0.17	11.90	0.53	0.07	0.11	0.00	98.21	-0.05	0.00	98.16
19-2-4a	52.76	0.46	5.09	16.71	10.66	0.23	11.91	0.41	0.09	0.04	0.02	98.38	-0.02	0.00	98.36
19-2-4c	54.50	0.19	2.88	18.09	9.91	0.29	11.91	0.17	0.07	0.12	0.00	98.13	-0.05	0.00	98.08
19-2-4f	51.83	0.43	6.07	16.20	11.15	0.22	11.76	0.53	0.11	0.09	0.00	98.39	-0.04	0.00	98.35

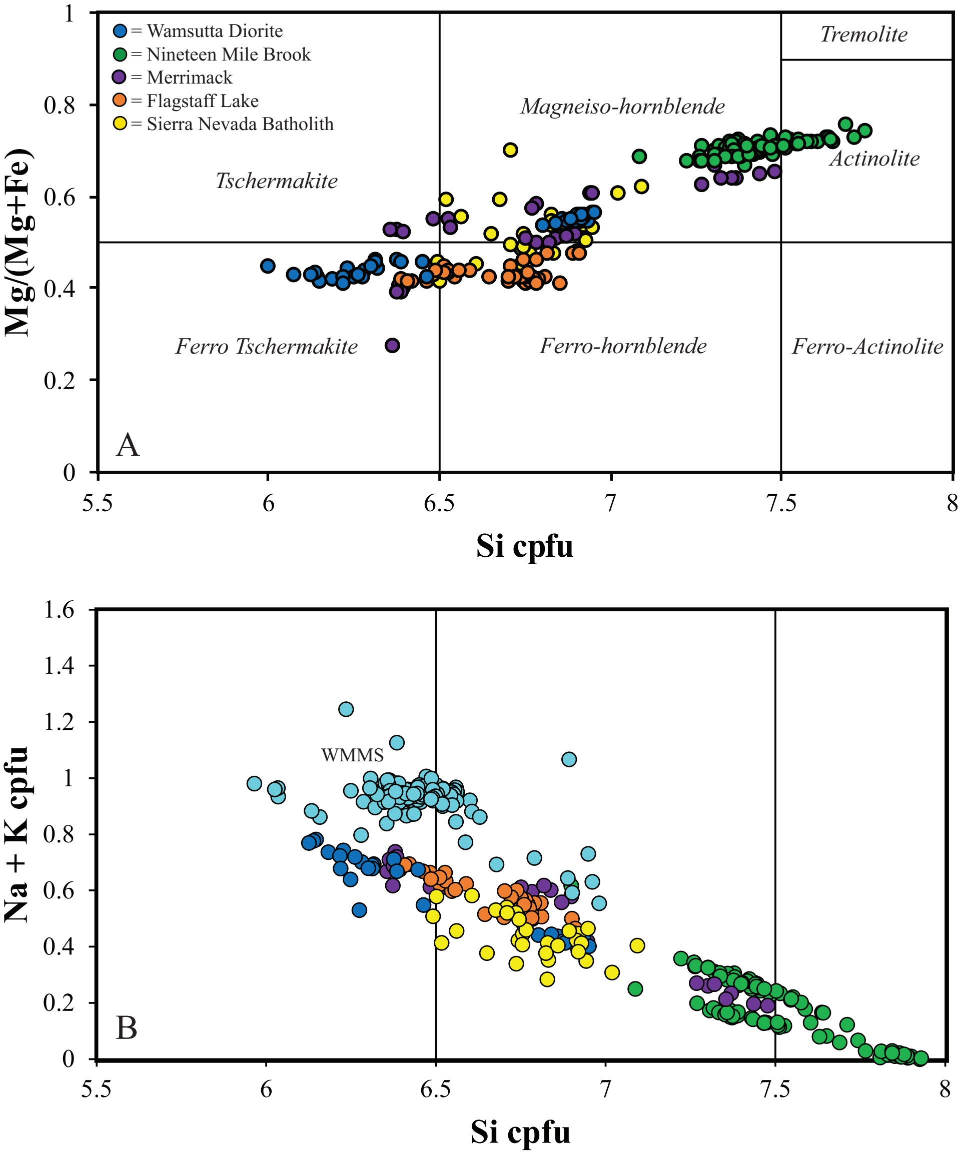

Fig. 3. (A) Mg/(Mg+Fe) versus Si (cations per formula unit based on 23 oxygens) showing compositions of amphibole in the Wamsutta Diorite, the Nineteenmile Brook Diorite, the Flagstaff Lake Igneous Complex, the diorites of the Merrimack trough, and the Sierra Nevada Batholith. (B) Na + K versus Si (cpfu). Amphiboles from calc-alkaline rocks have moderate alkali contents, defining a negative trend with increasing Si. The Nineteenmile Brook amphiboles plot along the trend defined by amphiboles of the Sierra Nevada Batholith and the Merrimack plutons. In contrast, amphiboles in the alkaline White Mountain Magma Series plot at higher alkali contents at equivalent Si values.

Lake, and Merrimack belt plutons, plotting as trachy-basalt and trachyandesites. The rocks of the Nineteenmile Brook Diorite are plutonic equivalents of basalt to basaltic andesite, overlapping the compositions of the Merrimack belt and Flagstaff Lake plutons. The more mafic rocks from the mingled zone in the Meredith Granite are trachyandesites.

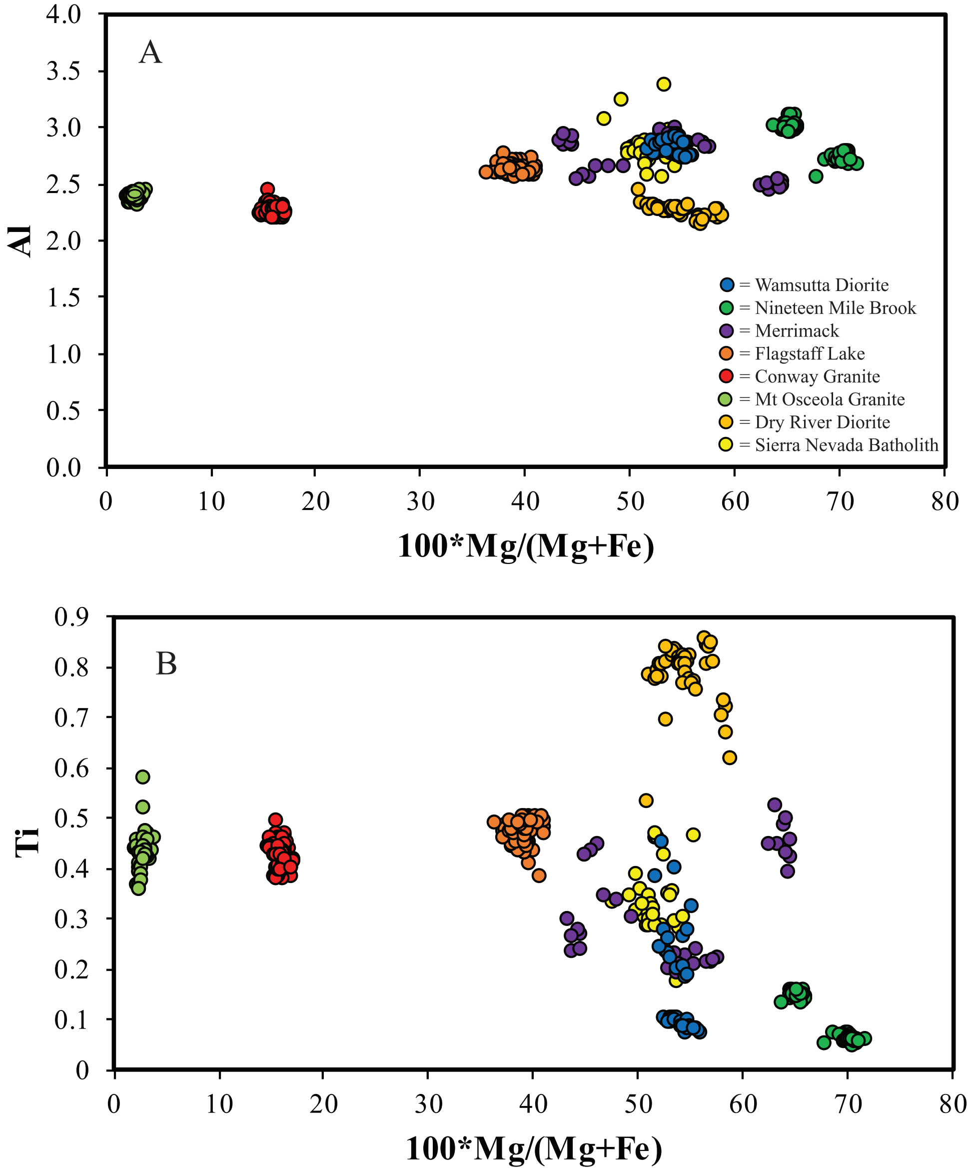

Fig. 4. Al (A) and Ti (B) versus 100Mg/(Mg+Fe) cpfu diagram showing biotite compositions of the Wamsutta Diorite and the Nineteenmile Brook Diorite compared to biotite in the Flagstaff Lake Igneous Complex, the calc-alkaline Merrimack trough diorites and the alkaline Dry River Diorite, the Mt Osceola and Conway Granites.

The MgO versus SiO_2 diagram (fig. 7) shows the most mafic rocks of the Wamsutta, Nineteenmile Brook, and Flagstaff Lake plutons have MgO contents between 3 and 7 wt.%. Most of the Merrimack belt plutons have similar SiO_2 contents but extend to higher MgO concentrations of 8 to 9 wt.%. The more mafic rocks of the mingled zones Kinsman Granodiorite mingled zones are the least rich in MgO (<3 wt.%).

TABLE 2

Representative biotite analyses, Wamsutta Diorite and Nineteenmile Brook Pluton

	SiO_2	TiO_2	Al_2O_3	MgO	FeO	MnO	CaO	Na_2O	K_2O	F	Cl	Total	F=O	Cl=O	Total
WS-1-1c	36.01	2.46	16.01	11.93	19.07	0.33	0.33	0.01	9.71	0.41	0.15	96.41	-0.17	-0.03	96.20
WS-2-1b	38.48	0.68	15.71	12.65	17.70	0.17	0.04	0.03	9.73	1.53	0.01	96.73	-0.65	0.00	96.08
WS-2-1d	37.72	0.75	15.74	12.76	18.43	0.15	0.02	0.03	9.75	1.42	0.01	96.80	-0.60	0.00	96.20
WS-2-1g	38.26	0.73	15.68	12.54	18.13	0.16	0.05	0.02	9.66	1.64	0.01	96.89	-0.69	0.00	96.20
WS-2-1h	37.96	0.72	15.69	12.73	17.88	0.14	0.03	0.07	9.75	1.64	0.01	96.61	-0.69	0.00	95.92
WS-2-1j	37.77	0.80	15.75	12.22	18.35	0.17	0.04	0.03	9.82	1.55	0.01	96.50	-0.65	0.00	95.85
WS-2-1k	37.97	0.69	15.72	12.78	18.88	0.17	0.06	0.04	9.27	1.42	0.01	96.99	-0.60	0.00	96.39
WS-2-2c	37.59	0.93	15.94	11.89	19.02	0.19	0.01	0.07	9.58	1.46	0.02	96.70	-0.61	-0.01	96.08
WS-2-2d	37.62	0.91	15.92	12.07	18.68	0.11	0.00	0.05	9.82	1.50	0.01	96.68	-0.63	0.00	96.05
WS-2-2e	37.86	0.95	16.17	11.82	18.50	0.21	0.02	0.05	9.79	1.51	0.01	96.88	-0.63	0.00	96.25
WS-2-2f	37.99	0.94	15.94	12.14	18.59	0.17	0.03	0.04	9.65	1.46	0.00	96.97	-0.62	0.00	96.35
WS-2-2g	37.95	0.93	15.97	12.04	18.87	0.13	0.01	0.05	9.76	1.52	0.02	97.24	-0.64	0.00	96.60
WS-2-2h	37.36	0.93	16.23	12.17	18.70	0.16	0.07	0.06	9.69	1.49	0.02	96.88	-0.63	0.00	96.24
WS-2-3a	37.69	0.89	15.99	12.12	18.52	0.13	0.02	0.04	9.77	1.35	0.02	96.54	-0.57	-0.01	95.96
WS-2-3c	37.36	0.85	16.27	11.97	18.74	0.23	0.01	0.03	9.45	1.14	0.00	96.04	-0.48	0.00	95.56
WS-2-3d	37.58	0.89	16.10	12.06	18.74	0.23	0.00	0.04	9.60	0.97	0.02	96.23	-0.41	0.00	95.82
WS-2-3h	38.19	0.89	15.90	12.28	18.02	0.20	0.00	0.03	9.78	1.27	0.00	96.56	-0.53	0.00	96.03
19-1-1e	37.57	0.65	15.79	16.64	12.98	0.19	0.00	0.04	10.40	2.52	0.01	96.78	-1.06	0.00	95.72
19-1-1g	37.98	0.65	16.01	16.41	12.61	0.18	0.01	0.05	10.45	2.47	0.00	96.82	-1.04	0.00	95.78
19-1-1i	37.74	0.66	16.04	16.66	13.05	0.17	0.00	0.04	10.39	2.53	0.01	97.29	-1.06	0.00	96.22
19-1-1o	37.79	0.53	15.94	16.82	12.85	0.22	0.00	0.04	10.54	2.43	0.02	97.18	-1.02	0.00	96.16
19-2-1o	38.59	1.36	17.38	15.19	14.77	0.13	0.32	0.21	7.57	0.18	0.04	95.74	-0.07	-0.01	95.65
19-2-1u	38.68	1.29	17.41	15.08	14.81	0.00	0.00	0.18	8.60	0.21	0.04	96.31	-0.09	-0.01	96.21
19-2-1v	38.45	1.39	17.65	15.07	14.62	0.00	0.03	0.16	8.40	0.16	0.05	95.97	-0.07	-0.01	95.89
19-2-1z	38.81	1.29	17.30	15.10	14.26	0.12	0.02	0.17	8.61	0.22	0.04	95.92	-0.09	-0.01	95.82
19-2-2a	38.83	1.30	17.54	15.19	14.29	0.05	0.00	0.15	8.57	0.25	0.04	96.21	-0.11	-0.01	96.09
19-2-2b	38.70	1.42	17.26	15.18	14.35	0.07	0.01	0.17	8.50	0.23	0.04	95.93	-0.10	-0.01	95.83
19-2-2d	38.38	1.39	17.30	15.12	14.68	0.06	0.00	0.20	8.55	0.22	0.03	95.92	-0.09	-0.01	95.83
19-2-2e	38.77	1.46	17.36	14.95	14.58	0.01	0.01	0.20	8.51	0.20	0.04	96.08	-0.08	-0.01	95.99
19-2-2f	38.52	1.43	17.38	15.09	14.65	0.11	0.00	0.18	8.57	0.27	0.03	96.23	-0.11	-0.01	96.11
19-2-2i	38.59	1.39	17.50	15.29	14.15	0.05	0.00	0.18	8.51	0.22	0.02	95.90	-0.09	-0.01	95.80
19-2-2k	38.88	1.34	17.34	15.00	14.51	0.07	0.02	0.20	8.57	0.13	0.04	96.11	-0.06	-0.01	96.04

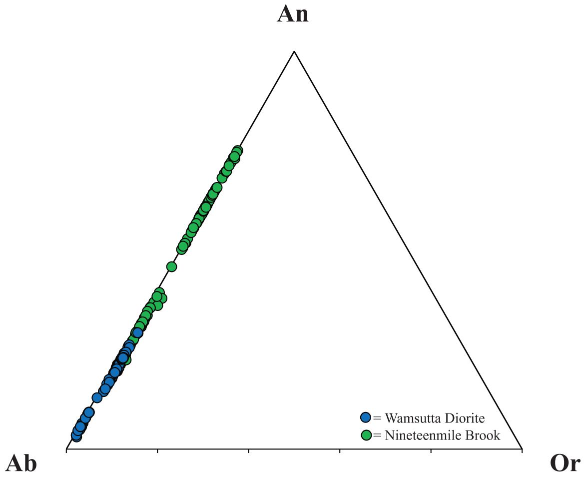

Fig. 5. An-Ab-Or diagram showing plagioclase compositions for the Wamsutta and Nineteenmile Brook diorites.

Chondrite-normalized REE patterns show arc basalt-like patterns for the Nineteenmile Brook Diorite and those of the Merrimack belt (fig. 8A). Merrimack samples have LREE abundances that average 100 times chondrite with HREE values between 10 and 30 times chondrite. Two Nineteenmile Brook samples have the same patterns, but two others have lower LREE abundances. $(La/Yb)_N$ values for these plutons range from 3.7 to 13.18, with small negative Eu anomalies present in the Merrimack trough samples and two of the Nineteenmile Brook samples. The mafic rocks of the Meredith Granite mingled zone have higher REE patterns than both the Nineteenmile Brook and Merrimack belt plutons but are parallel to those patterns and display more prominent negative Eu anomalies. In contrast to all these, the patterns for the Wamsutta Pluton are much steeper. LREE values approach 500 times chondrites and the HREE abundances are the lowest of the rocks studied here, yielding $(La/Yb)_N$ values between 91 and 126. The Flagstaff Lake Igneous Complex patterns have similar LREE concentrations as the Merrimack and Nineteenmile Brook plutons (fig. 8B), but are enriched in HREE, leading to flatter patterns.

The spider diagram (fig. 9A) shows similar relationships. The Nineteenmile Brook and Merrimack belt plutons have the same patterns with significant negative Nb anomalies, indicative of arc basalt compositions. The Meredith Granite mafic rocks have parallel but enriched arc-like patterns compared to the Merrimack and Nineteenmile Brook rocks and display prominent negative Sr and Ti anomalies as well as negative Nb anomalies. The Wamsutta Pluton has positive Ba and Sr anomalies, typically interpreted as indicating feldspar accumulation. However, none of the Wamsutta samples have high Al_2O_3 contents (table 4) or positive Eu anomalies (fig. 9C) that would support a feldspar accumulation interpretation, and potassium feldspar is not present in the rocks to account for the high Ba concentrations.

The high Sr concentrations of the Wamsutta Pluton are especially evident in the Sr versus La/Yb diagram (fig. 10A). The Wamsutta rocks contain up to 4000 ppm Sr and very high La/Yb ratios of 85 to 125, indicating that the Wamsutta Pluton has adakite-like compositions. In contrast, the Meredith Granite mafic rocks, the Nineteenmile Brook Pluton, the Flagstaff Lake, and the Merrimack belt plutons all display considerably lower Sr contents of generally less than 500 ppm and La/Yb ratios of less than 10.

TABLE 3

Representative plagioclase analyses, Wamsutta Diorite and Nineteenmile Brook Pluton

	Na_2O	Al_2O_3	SiO_2	K_2O	CaO	FeO	Total	Ab	Or	An
WS-1-2a	11.55	21.06	66.32	0.11	1.24	0.11	100.37	93.87	0.56	5.57
WS-1-2c	11.95	20.65	66.70	0.14	0.68	0.04	100.16	96.22	0.76	3.03
WS-1-2d	11.37	20.98	66.16	0.11	1.05	0.02	99.67	94.60	0.57	4.83
WS-1-2e	11.76	20.70	66.76	0.08	0.77	0.02	100.09	96.10	0.43	3.48
WS-1-2f	11.54	21.51	65.17	0.08	1.47	0.00	99.77	93.04	0.40	6.56
WS-1-2h	11.49	21.03	66.19	0.04	1.43	0.00	100.18	93.36	0.23	6.41
WS-1-2i	11.08	21.92	64.96	0.06	2.06	0.05	100.12	90.42	0.30	9.28
WS-1-3a	10.92	20.01	67.87	0.07	1.18	0.14	100.18	94.01	0.39	5.60
WS-1-3b	11.72	21.22	65.77	0.06	1.32	0.06	100.15	93.87	0.30	5.83
WS-1-3d	10.88	21.27	65.93	0.06	1.89	0.09	100.11	90.95	0.31	8.74
WS-1-3e	11.39	21.76	64.82	0.06	1.73	0.14	99.89	92.00	0.30	7.71
WS-1-3f	11.55	21.29	65.93	0.05	1.25	0.09	100.16	94.10	0.26	5.64
WS-1-3h	10.94	22.00	64.65	0.06	2.01	0.04	99.71	90.46	0.35	9.19
WS-2-1b	8.31	25.36	60.03	0.13	5.39	0.05	99.26	73.08	0.73	26.19
WS-2-1c	8.80	24.37	61.61	0.12	5.11	0.03	100.04	75.16	0.70	24.15
WS-2-2j	9.33	23.62	62.72	0.13	4.38	0.03	100.21	78.82	0.74	20.43
WS-2-2m	9.82	23.11	63.58	0.16	3.55	0.00	100.21	82.64	0.88	16.49
WS-2-2p	9.14	23.97	62.51	0.14	4.47	0.03	100.27	78.11	0.79	21.11
WS-2-2q	9.35	23.64	62.91	0.17	4.36	0.02	100.45	78.76	0.94	20.31
WS-2-3d	9.00	24.47	61.90	0.16	4.80	0.00	100.33	76.54	0.90	22.56
WS-2-3g	9.02	24.38	61.75	0.18	4.91	0.02	100.26	76.12	0.98	22.90
19-1-1b	8.65	25.27	60.43	0.12	5.55	0.02	100.04	73.33	0.67	26.00
19-1-1c	8.25	25.54	59.81	0.13	6.36	0.00	100.09	69.62	0.74	29.65
19-1-1d	8.25	25.86	59.64	0.15	6.27	0.02	100.19	69.83	0.83	29.35
19-1-1e	6.99	27.42	57.39	0.13	8.30	0.06	100.29	59.92	0.73	39.35
19-1-1f	7.49	26.69	57.79	0.11	7.51	0.03	99.62	63.95	0.61	35.44
19-1-1g	7.41	26.82	57.43	0.12	7.58	0.02	99.39	63.44	0.69	35.87
19-1-2a	8.28	25.40	59.93	0.14	6.14	0.05	99.94	70.40	0.77	28.84
19-1-2b	8.46	25.47	60.39	0.18	5.83	0.00	100.32	71.69	1.01	27.30
19-1-2c	8.38	25.31	60.32	0.16	5.73	0.02	99.93	71.90	0.90	27.20
19-1-2f	9.11	24.25	61.67	0.22	4.68	0.02	99.94	76.92	1.24	21.85
19-1-2g	9.07	24.22	61.95	0.21	4.81	0.02	100.29	76.42	1.19	22.39
19-1-2h	7.72	26.13	58.78	0.15	6.89	0.12	99.79	66.39	0.84	32.77
19-1-2i	7.79	26.47	58.46	0.12	6.97	0.02	99.81	66.47	0.65	32.88
19-1-2n	8.08	25.47	59.08	0.20	6.13	0.07	99.03	69.68	1.14	29.18
19-1-3a	8.02	25.75	59.01	0.19	6.54	0.11	99.62	68.18	1.08	30.73
19-1-3b	7.33	26.96	57.64	0.14	7.85	0.06	99.99	62.32	0.80	36.88
19-1-3c	7.25	27.08	57.68	0.36	7.65	0.05	100.07	61.92	2.01	36.07
19-1-3d	7.12	27.52	57.30	0.12	8.11	0.04	100.20	60.94	0.70	38.36
19-1-3e	7.61	26.41	58.98	0.17	7.06	0.00	100.23	65.47	0.96	33.58
19-1-3f	9.30	24.19	61.93	0.18	4.63	0.02	100.23	77.66	0.98	21.36
19-1-3g	9.19	24.43	61.97	0.19	4.60	0.00	100.37	77.51	1.06	21.44
19-1-3h	8.90	24.15	61.17	0.34	4.76	0.00	99.33	75.70	1.90	22.40
19-1-3k	7.47	27.09	57.64	0.12	7.53	0.06	99.91	63.80	0.69	35.51

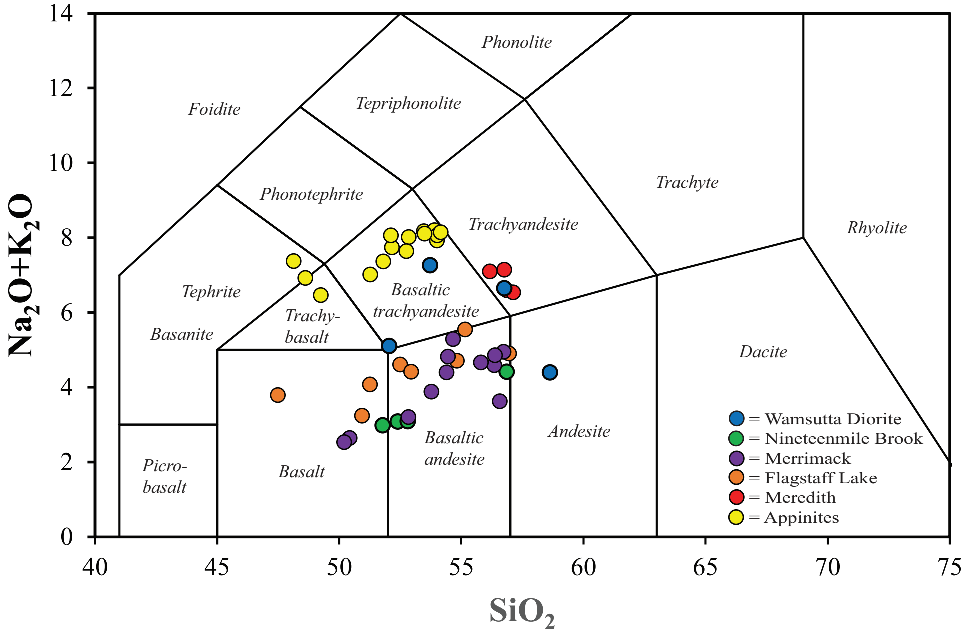

Fig. 6. Total alkali versus SiO_2 diagram showing the compositions of the Wamsutta and Nineteenmile Brook diorites compared to diorites of the Flagstaff Lake Igneous Complex, the Merrimack trough, the mafic rocks of the Meredith Porphyritic Granite, and the Scottish appinites at Ach'Uaine (Fowler and Henney, 1996).

Distinctions between the Wamsutta Pluton and all the other studied rocks is also evident in the $(La/Yb)_N$ versus Yb_N plot (fig. 10B) and the Sr/Y versus Y plot (fig. 10C) where the Wamsutta Pluton rocks show high $(La/Yb)_N$ and Sr/Y values similar to adakites. In contrast, the Nineteenmile Brook, Meredith Granite mafic rocks, Flagstaff Lake, and the Merrimack belt plutons all have low Sr/Y and $(La/Yb)_N$ values, compositions more compatible with calc-alkaline systems (Richards and Kerrich, 2007).

The Hf/3–Th–Ta diagram Tectonic discrimination diagram shows that the Wamsutta, Nineteenmile Brook, Flagstaff Lake, and the Merrimack belt plutons plot largely in the field of volcanic arc basalts (fig. 11A), in agreement with the subduction zone signature of these rocks with negative Nb anomalies in figure 9. Similarly, the Nineteenmile Brook, Flagstaff Lake, and Merrimack belt plutons plot in and adjacent to the volcanic arc basalt field in the 2Nb-Zr/4-Y diagram (fig. 11B). However, the Wamsutta Pluton, because of its low Y concentrations, plots as within-plate basalts in this diagram, demonstrating the inappropriateness of using this diagram for rocks of adakitic compositions. In the Nb/La versus La/Yb diagram (fig. 12A), most of the samples plot in the continental arc field (after Hollocher and others, 2012). The rocks plot along the boundary between continental and alkaline arcs in the Th/Yb versus La/Yb diagram (fig. 12B). The arc-like signature of all these rocks is displayed in the Th/Yb versus Ta/Yb diagram (fig. 13A) where all the rocks plot above the MORB-OIB array (Pearce, 2008), indicating subduction zone and/or crustal contributions to the magmas. In the Ce/Nb versus Th/Nd diagram (fig. 13B), the Merrimack trough plutons plot at considerably higher Th/Nb and Ce/Nb values than the Nineteenmile Brook, Flagstaff Lake, and mafic rocks of the Meredith Granite. The average of later

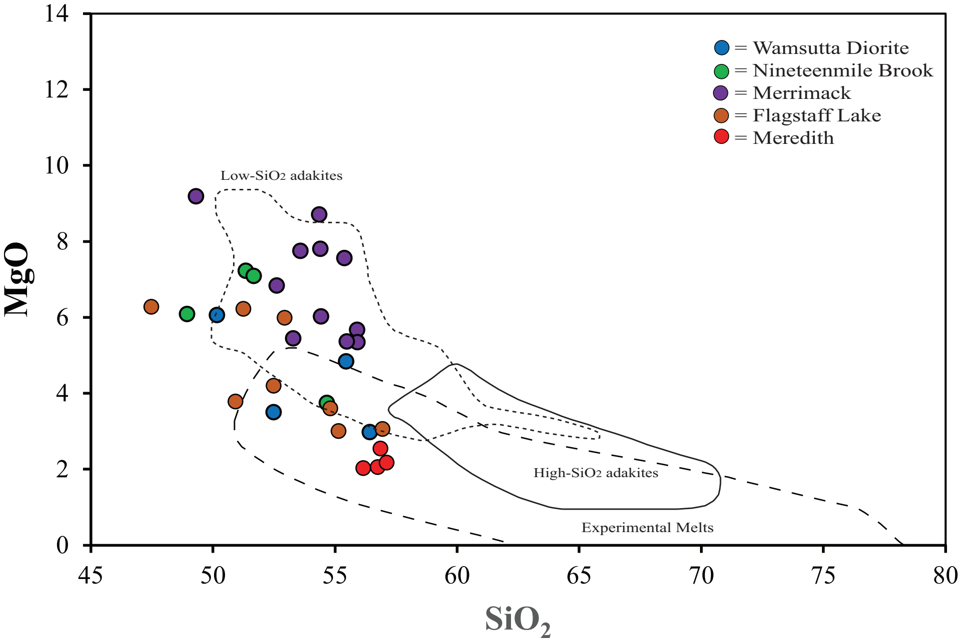

Fig. 7. MgO verus SiO_2 diagram showing the compositions of the Wamsutta and Nineteenmile Brook diorites compared to diorites of the Flagstaff Lake Igneous Complex, the Merrimack trough, and the mafic rocks of the Meredith Porphyritic Granite. The field for low SiO_2 and high SiO_2 adakites is presented as is the high-pressure field for experimental melts of basaltic rocks (Rapp and others, 1991; Rapp and Watson, 1995; Wolf and Wyllie, 1994).

group plot along a Th/Ce trend of 0.06 versus 0.12 of the Merrimack rocks. The Wamsutta Diorite has the lowest Th/Ce value of 0.01.

In the Ce/Yb versus La/Ta diagram (fig. 14A; Dorais and others, 2017), the Nineteenmile Brook, Flagstaff Lake, and the Merrimack belt plutons plot at relatively constant Ce/Yb ratios at values along the boundary of partial melts from garnet peridotite and spinel peridotite source rocks (Ellam, 1992). Leat and others (1988) interpret rocks with La/Ta values of less than 22 as partial melts of asthenospheric sources that have undergone little to no contamination from the mantle lithosphere or the continental crust. Thompson and Morrison (1988) proposed that values between 22 and 30 indicate no crustal contamination, but some lithospheric mantle contamination is possible. Values greater than 30 indicate significant amounts of mantle lithospheric and/or crustal contamination. Nineteenmile Brook, Flagstaff Lake, and Merrimack trough diorites have La/Ta values ranging between 12 and 100, forming a trend in figure 14A that extends from values suggestive of partial melting of the asthenosphere to sources with significant crustal/lithospheric mantle contamination (Fitton and others, 1988; Leat and others, 1988; Thompson and Morrison, 1988). The Wamsutta Pluton has the highest La/Ta values indicative of considerable crustal contamination. The very high Ce/Yb values suggest a garnet peridotite source, deeper than the other studied rocks.

Likewise, the $(Dy/Yb)_N$ versus $(La/Yb)_N$ diagram (fig. 14B; Azizi and others, 2019) shows the Wamsutta Diorite plotting at high $(Dy/Yb)_N$ values, adjacent to the garnet lherzolite melting line. These samples form a near vertical trend with variable $(Dy/Yb)_N$ values, following the vector for partial melting over increasing pressures, or variable trace element enrichments of the source. In contrast, the Nineteenmile

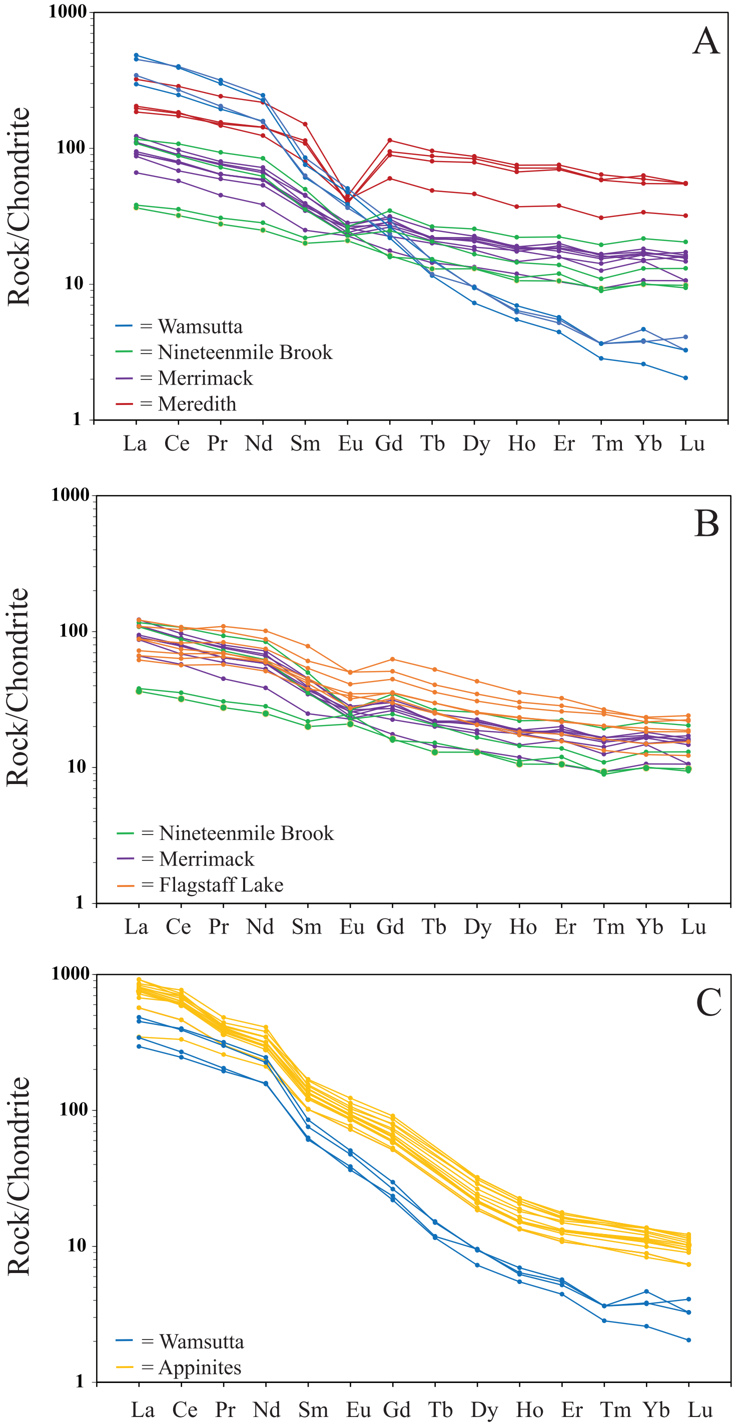

Fig. 8. (A) Chondrite-normalized REE patterns for the Wamsutta and Nineteenmile Brook diorites compared to patterns of the diorites of the Merrimack trough and the mafic rocks of the Meredith Porphyritic Granite (normalization constants of Anders and Ebihara, 1982). (B) Normalized patterns for the Flagstaff Lake Igneous complex compared to those of the Nineteenmile Brook and Merrimack belt plutons. (C) Normalized patterns of the Wamsutta Diorite compared to those of the Ach'Uaine appinites (Fowler and Henney, 1996).

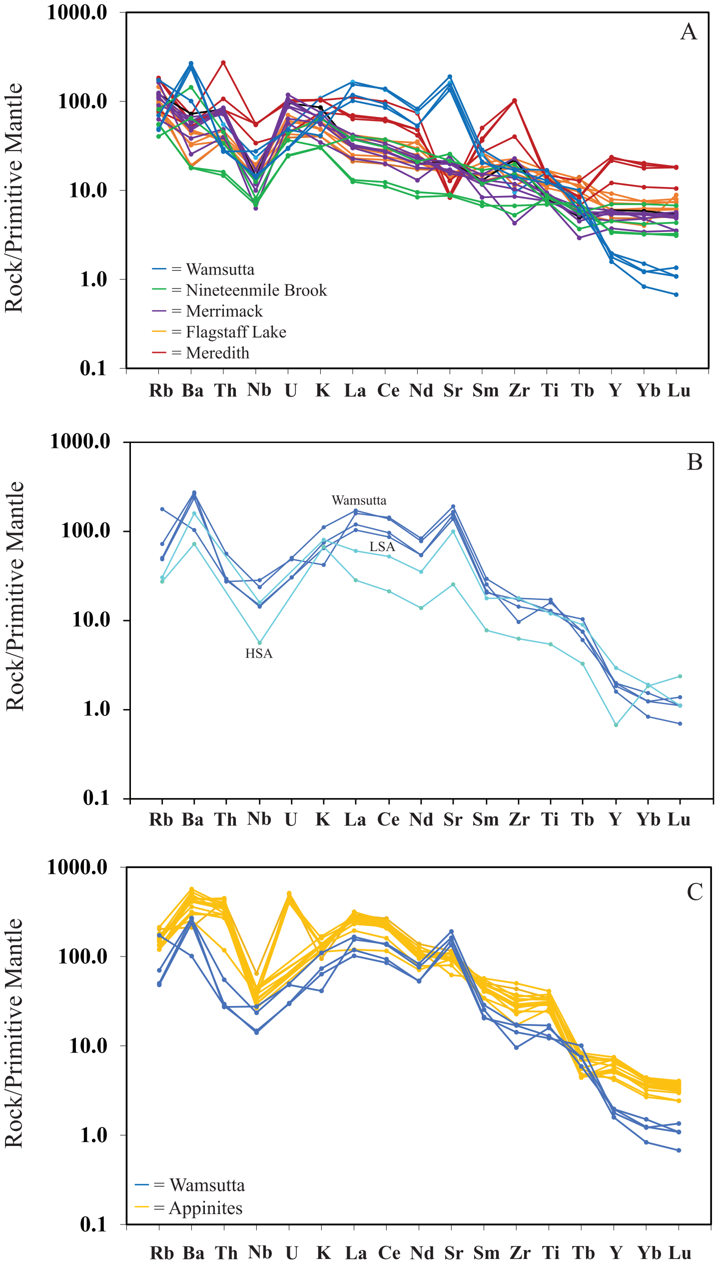

Fig. 9. (A) Spider diagram for the Wamsutta and Nineteenmile Brook diorites compared to patterns of the diorites of the Flagstaff Lake Igneous Complex, Merrimack trough and the mafic rocks of the Meredith Porphyritic Granite (normalization constants of McDonough and others, 1992). (B) Patterns for the Wamsutta Diorite compared to average patterns for low and high SiO_2 adakites (LSA and HSA respectively; Martin and others, 2005). (C) Normalized patterns of the Wamsutta Diorite compared to those of the Ach'Uaine appinites (Fowler and Henney, 1996).

TABLE 4

Major and Trace Element Analyses, Wamsutta, Nineteenmile Brk, Meredith, Merrimack Plutons

	WS-1	WS-2	WS-3	WS-4	19-1	19-2	19-3	19-4	MPG-10	MPG-13	MPG-14
SiO_2	50.17	52.49	55.45	56.43	54.67	51.35	51.67	48.94	56.86	56.75	56.16
TiO_2	1.61	1.62	1.45	1.28	0.8	1.6	1.35	1.21	1.46	1.84	1.79
Al_2O_3	15.68	16.46	15.54	16.46	16.9	17.91	18.18	16.37	18.42	17.44	17.26
Fe_2O_3	7.61	8.5	4.57	5.46	9.18	7.98	7.5	11.11	7.83	9.38	9.46
MnO	0.11	0.09	0.08	0.08	0.17	0.15	0.15	0.17	0.14	0.16	0.16
MgO	6.06	3.5	4.84	2.98	3.75	7.23	7.09	6.09	2.55	2.06	2.03
CaO	10.18	7.95	8.28	9.49	7.99	9.62	9.85	10.08	4.98	3.86	3.7
Na_2O	3.01	3.80	4.29	2.99	2.31	2.11	2.11	1.89	4.34	3.96	3.96
K_2O	1.91	3.3	2.21	1.24	1.94	0.91	0.92	0.93	2.25	3.18	3.14
P_2O_5	1.373	0.715	0.999	1.214	0.258	0.068	0.069	0.392	0.6	0.73	0.68
LOI	1.3	0.71	1.39	1.37	1.81	0.91	1.03	2.65	-	-	-
Total	99.01	99.14	99.10	98.99	99.78	99.84	99.92	99.83	99.43	99.36	98.34
Rb	110	31.8	30.5	44.5	51.9	34.8	35.2	25.7	49.6	117	113
Sr	2840	3420	3230	4010	541	183.5	190.5	454	270	182	175.5
Ba	707	1845	1645	1880	1010	126	124.5	454	366	404	388
La	69.7	114	81	106.5	25.6	8.6	9	27.5	48.1	43.6	46.5
Ce	151.5	241	165.5	246	54	19.7	21.9	66.3	113	106.5	111
Pr	18.05	27.8	18.95	29.4	6.71	2.57	2.85	8.65	13.6	14.05	14.4
Nd	72.4	103	71.3	112	28.4	11.4	12.9	38.5	56.5	65.1	65.3
Sm	9.07	11.25	9.34	12.7	5.27	2.98	3.26	7.44	11.85	16.95	16.15
Eu	2.16	2.66	2.04	2.83	1.27	1.17	1.38	1.48	2.35	2.24	2.21
Gd	4.31	5.19	4.62	5.84	4.87	3.2	3.11	6.84	11.8	18.6	17.5
Tb	0.41	0.54	0.42	0.53	0.73	0.46	0.54	0.94	1.73	3.11	2.85
Dy	1.78	2.29	2.34	2.31	4.07	3.18	3.21	6.24	11.3	20.5	19.25
Ho	0.3	0.38	0.34	0.35	0.79	0.58	0.61	1.21	2.03	3.91	3.66
Er	0.71	0.91	0.83	0.88	2.21	1.69	1.91	3.57	6.04	11.45	11.15
Tm	0.07	0.09	0.09	0.09	0.27	0.23	0.22	0.48	0.76	1.45	1.44
Yb	0.41	0.61	0.6	0.74	2.07	1.58	1.6	3.44	5.37	10	8.75
Lu	0.05	0.08	0.1	0.08	0.32	0.24	0.23	0.5	0.78	1.35	1.34
Zr	189	107	159	194	152	117	69	60	451	1140	1150
Y	7.2	8.9	8.1	8.9	20.5	15.2	15.7	31.8	55.4	106	99
Hf	4.6	3.1	4	4.6	4.4	2	1.5	5.6	10.7	22.5	23.2
Nb	10.5	16.7	10	19.6	5.8	5.3	4.9	8.9	24.2	39.7	39
Ta	0.2	0.9	0.1	0.9	0.6	0.5	0.3	0.4	1.8	3.2	3.1
Th	2.38	4.68	2.49	2.32	3.85	1.37	1.25	2.87	7.1	6.83	9.07
U	0.62	1.04	0.63	1.01	0.92	0.51	0.52	0.77	0.91	2.02	2.17
Pb	1.7	2.4	2.2	2.4	5.6	2.5	1.5	1.3	0.3	-	-
V	225	193	141	196	225	324	332	295	129	-	-
Cr	108	2	81	1	21	18	281	291	30	6	7
Ni	74	9	80	8	13	18	23	20	-	18	15
Ga	26.1	25.6	24	23.8	20	19.7	20.9	19.1	28.2	29.9	29.3
Zn	141	129	91	128	88	104	63	64	-	150	145
Sc	23	12	14	13	28	10	37	37	-	24	24

Brook Pluton, Flagstaff Lake, and those of the Merrimack belt plot along the spinel lherzolite melting line.

Table 4

(continued)

	MPG-18	D4*	D11*	E2*	E3*	E4*	E5*	S1*	S4*	S11*	S12*
SiO_2	57.12	49.75	49.31	54.40	54.82	53.58	55.91	54.43	55.38	55.92	55.48
TiO_2	1.85	1.04	0.98	1.09	0.98	1.14	1.17	1.07	0.63	1.26	1.40
Al_2O_3	16.76	16.70	17.41	14.75	14.32	14.84	16.59	18.06	16.88	17.25	16.82
Fe_2O_3	9.46	8.83	8.29	8.80	9.13	9.18	8.31	7.29	7.26	7.52	7.64
MnO	0.16	0.17	0.16	0.18	0.18	0.17	0.16	0.15	0.22	0.15	0.15
MgO	2.18	10.06	9.19	7.81	8.71	7.75	5.67	6.03	7.56	5.35	5.37
CaO	4.09	10.87	11.78	7.47	7.75	8.54	7.63	7.45	7.98	7.38	7.43
Na_2O	3.44	2.12	2.09	2.69	2.60	2.30	2.90	2.84	2.51	2.94	2.86
K_2O	3.1	0.49	0.40	2.57	2.25	2.03	1.66	1.71	1.04	1.94	1.92
P_2O_5	0.709	0.17	0.20	0.30	0.27	0.29	0.26	0.27	0.11	0.23	0.24
LOI	0.83	1.52	1.58	0.52	0.32	1.31	1.02	1.74	1.67	1.36	0.90
Total	99.70	100.20	99.81	100.05	101.01	99.83	100.26	99.30	99.58	99.94	99.31
Rb	111.5	8.7	5.8	76.4	77.5	68.3	57.3	104	39.9	71.2	79.2
Sr	190.5	597	695	440	430	419	442	363	507	326	340
Ba	491	184.5	141.5	505	421	402	467	178.5	269	333	350
La	76	10.3	11.2	21.4	22.3	21.5	26.1	20.6	15.6	26.1	28.9
Ce	176	26.1	30.6	48.6	49.3	48.1	55.3	42.1	35.4	55.2	59.6
Pr	22.4	3.65	4.34	5.95	5.99	5.97	7.02	5.52	4.19	7.16	7.4
Nd	99.6	18.2	22.4	27	26.7	26.6	30.2	24.3	17.6	31.1	32.9
Sm	22.4	3.81	4.24	38.59	37.11	36.11	44.77	34.7	24.9	39.19	45.23
Eu	2.5	1.17	1.43	1.34	1.49	1.29	1.58	1.45	1.27	1.43	1.5
Gd	22.5	4.05	4.36	5.69	5.35	5.18	5.93	4.43	3.46	5.65	6.19
Tb	3.39	0.53	0.66	0.78	0.78	0.74	0.76	0.71	0.51	0.78	0.89
Dy	21.3	3.57	4.15	5.39	5.06	4.58	5.27	4.38	3.27	5.13	5.52
Ho	4.11	0.57	0.8	1.01	0.95	0.97	1.04	0.8	0.65	0.99	1.03
Er	12.05	1.93	2.26	2.96	3.07	2.52	2.8	2.54	1.67	2.92	3.2
Tm	1.58	0.23	0.29	0.41	0.41	0.35	0.38	0.31	0.23	0.39	0.4
Yb	9.44	1.49	2.01	2.89	2.74	2.62	2.63	2.35	1.69	2.68	2.39
Lu	1.35	0.21	0.26	0.4	0.38	0.36	0.42	0.26	0.26	0.39	0.39
Zr	1135	74	78	74	73	79	120	70	105	140	156
Y	108	16.1	19.9	27.2	25.4	24.4	26.4	20.7	17	25.3	27
Hf	22.3	1.8	1.6	6.2	4.3	3.3	6.3	1.3	2.7	3.5	4
Nb	39.3	3.6	4.3	10.2	8.5	8.9	12.1	7.1	4.5	8.4	9.4
Ta	2.8	0.5	0.1	1	0.6	0.7	1.3	0.3	0.5	0.7	0.7
Th	23.3	0.49	0.24	6.88	7.23	6.1	6.19	3.36	4.13	6.71	7.13
U	2.1	0.28	0.1	2	2.49	1.86	1.83	1.34	1.19	2.09	2.23
Pb	-	-	-	-	-	-	-	-	-	-	-
V	119	158	166	191	199	207	189	167	128	142	159
Cr	4	320	380	370	430	310	180	180	270	150	180
Ni	11	44	32	134	166	117	55	24	20	6	10
Ga	28.7	18	18.9	18.3	18.5	19.4	22.2	21.9	19.7	21.4	21.1
Zn	121	71	68	90	88	86	92	85	81	76	81
Sc	23	0	6	20	0	25	20	27	12	5	11

* Major and selected trace elements previously published in Watts et al., 2000

DISCUSSION

Nineteenmile Brook Pluton

The undated Nineteenmile Brook Pluton has bearing on the subduction zone polarity during the Acadian Orogeny. First, it has amphibole and biotite compositions

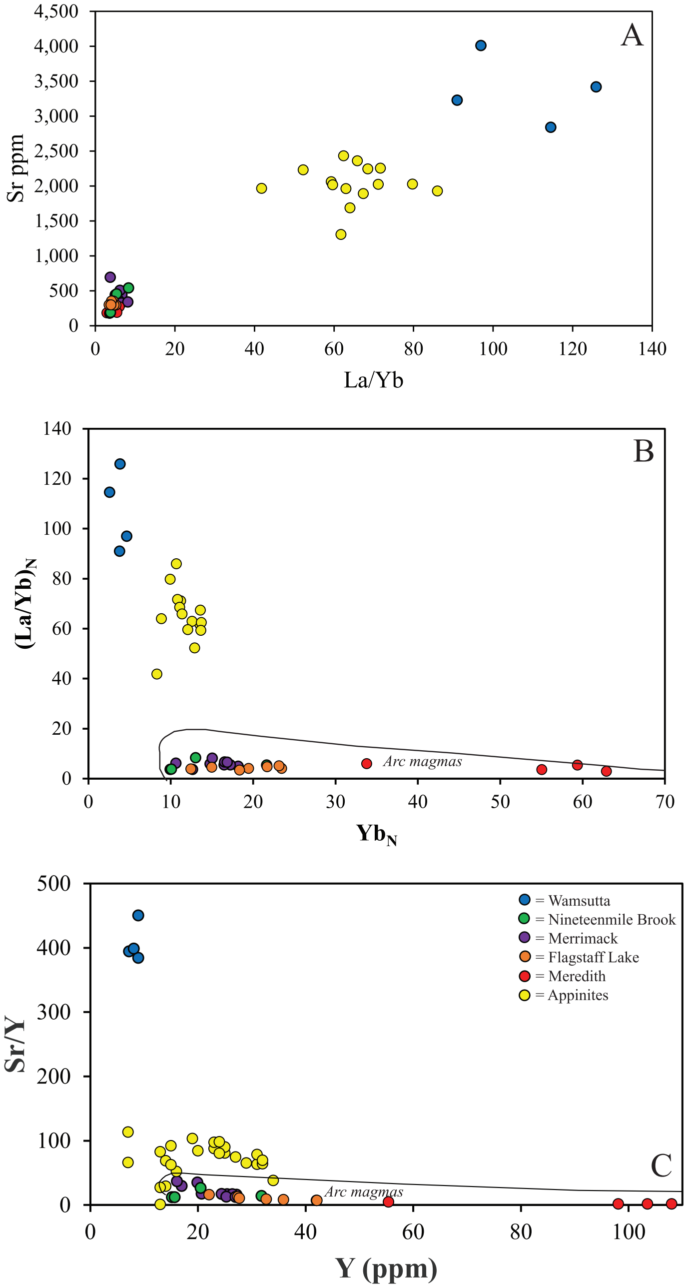

Fig. 10. (A) Sr (ppm) versus La/Yb diagram for the Wamsutta and Nineteenmile Brook diorites compared to patterns of the diorites of the Flagstaff Lake Igneous Comlex, the Merrimack trough, and the mafic rocks of the Meredith Porphyritic Granite. The Ach'Uaine appinites of Scotland (Fowler and Henney, 1996) also have high Sr concentrations. (B) $(La/Yb)_N$ versus Yb_N diagram for the Wamsutta and Nineteenmile Brook diorites compared to patterns of the diorites of the Merrimack trough and the mafic rocks of the Meredith Porphyritic Granite. The Ach'Uaine appinites of Scotland also have high $(La/Yb)_N$ values, similar to adakites. (C) Sr/Y versus Y (ppm) diagram for the Wamsutta and Nineteenmile Brook diorites compared to patterns of the diorites of the Merrimack trough and the mafic rocks of the Meredith Porphyritic Granite. The Ach'Uaine appinites of Scotland also have relatively high Sr/Y similar to adakites.

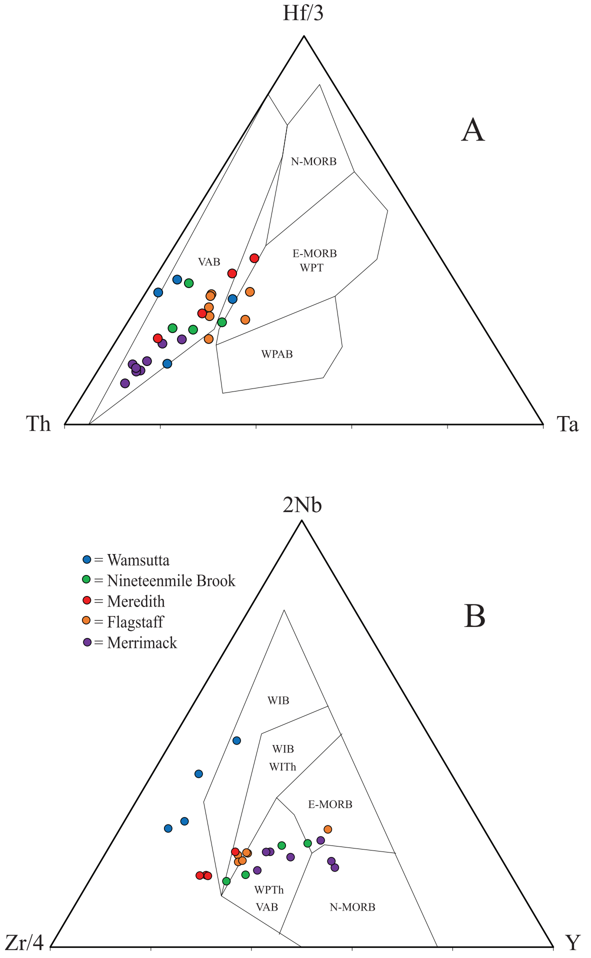

Fig. 11. (A) Hf/3-Th-Ta tectonic discrimination diagram (Wood, 1980) showing the Wamsutta, Nineteenmile Brook, Meredith Granite mafic rocks, Flagstaff Lake, and Merrimack trough diorites all plotting in and adjacent to the volcanic arc basalt field. (B) 2Nb-Ar/4-Y tectonic discrimination diagram (Meschede, 1986) showing the Nineteenmile Brook, Flagstaff Lake, Meredith Granite mafic rocks, and Merrimack trough diorites plotting in and adjacent to the volcanic arc basalt field whereas the Wamsutta Diorite plots in and adjacent to the within plate basalt field.

that are similar to calc-alkaline plutons of New Hampshire with ages of ~407 to 410 Ma, indicating that the Nineteenmile Brook Pluton is not a member of the younger, alkaline, White Mountain Magma Series (figs. 3 and 4). It also has whole-rock compositions similar to the calc-alkaline Exeter, Sweepstakes, and Island Pond diorites of the Merrimack belt. Chondrite-normalized REE patterns (fig. 8), spider diagrams (fig. 9A), $(La/Yb)_N$ versus Yb_N values (fig. 10B), Sr/Y versus Y values (fig. 10C), tectonic discrimination diagrams (figs. 11 and 12), and Th/Yb versus Nb/Yb ratios (fig. 13A) all indicate that these rocks have arc basalt trace element affinities. Additionally, the mafic rocks from the mingled zone in the Meredith Porphyritic Granite also have arc signatures, and being contemporaneous with the host granites, have an age of ~410 Ma (Lyons and others, 1997). The location of the Nineteenmile Brook pluton and the Meredith Porphyritic Granite in the interior

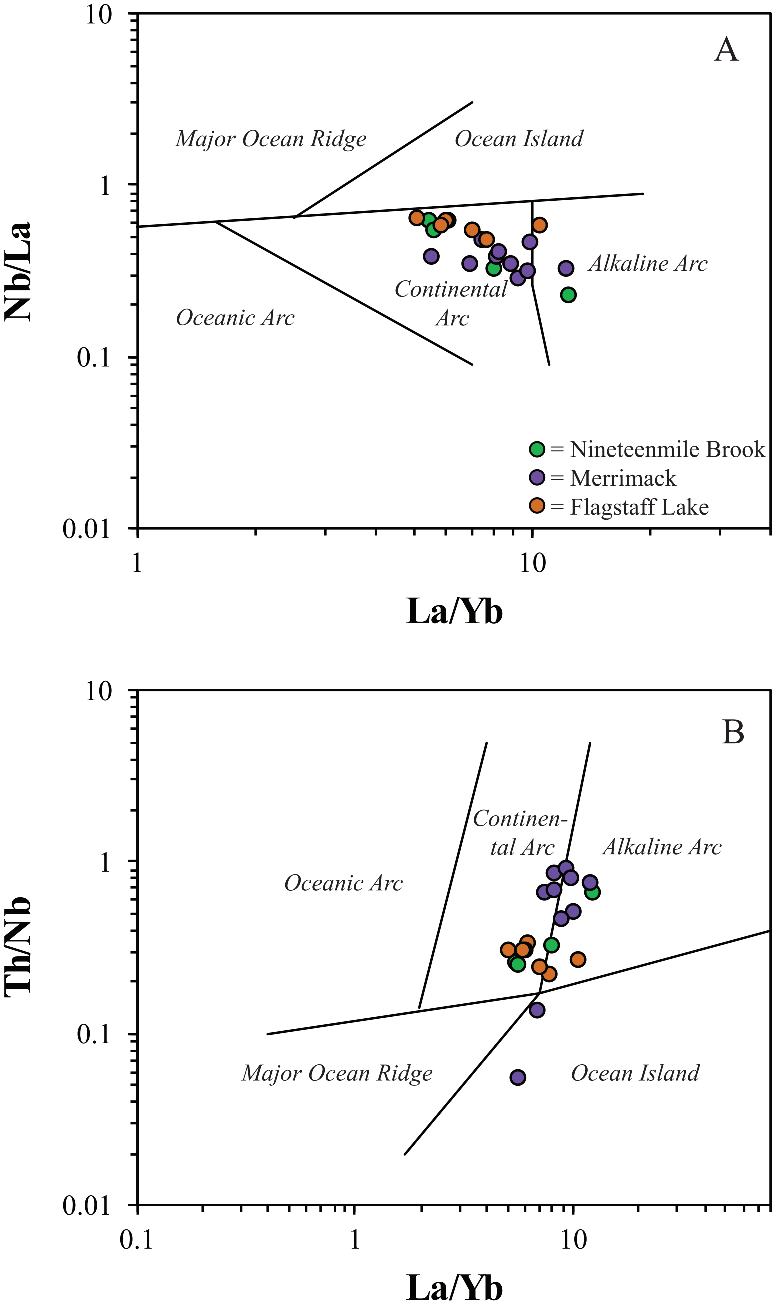

Fig. 12. (A) Nb/La versus La/Yb diagram (Hollocher and others, 2012) showing that most of the rocks of the Merrimack trough, Nineteenmile Brook, and Flagstaff Lake plot in the continental arc field. (B) Th/Nb versus La/Yb diagram (Hollocher and others, 2012) where most of the rocks plot along the boundary between the continental arc and alkaline arc fields.

of Central Maine trough, inboard of the arc plutons of the peri-Gondwanan Merrimack belt (Wintsch and others, 2007), can be interpreted as evidence for a westerly dipping subduction zone.

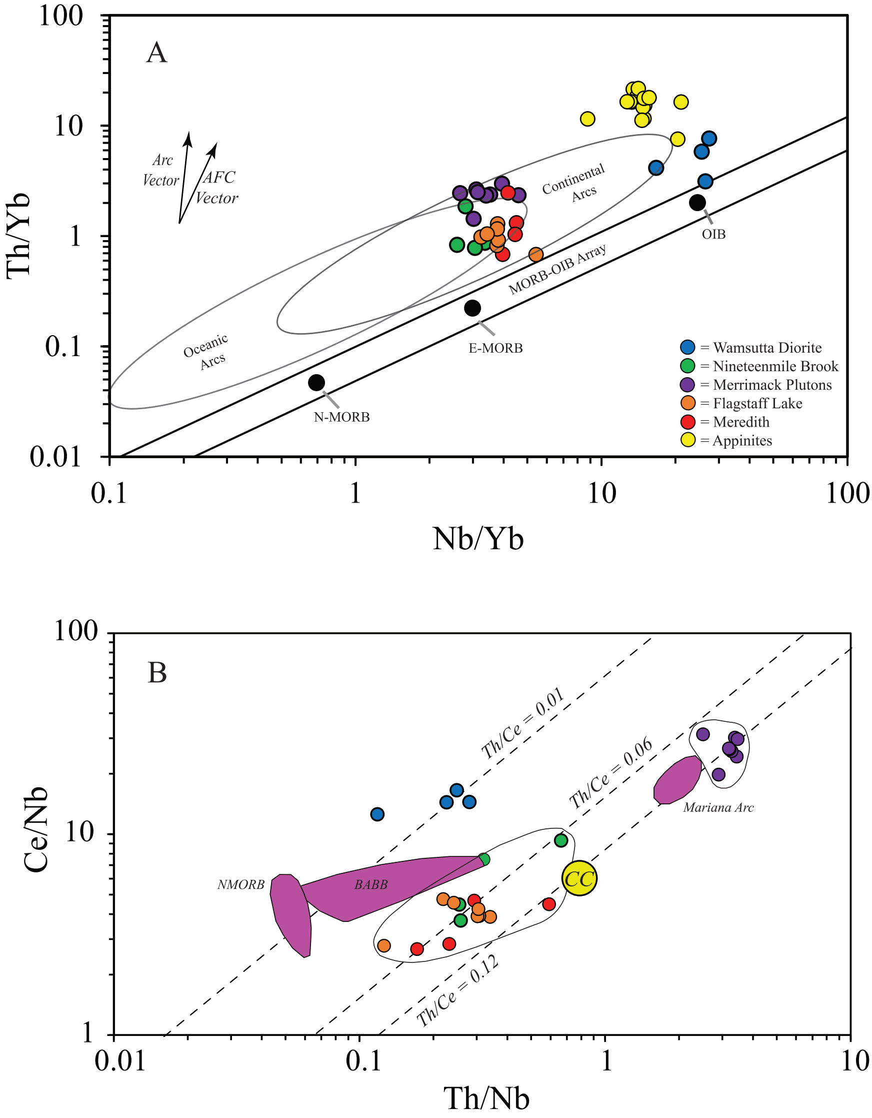

Fig. 13. (A) Th/Yb versus Nb/Yb diagram (Pearce, 2008) showing that the Nineteenmile Brook and Wamsutta plutons plot above the MORB-OIB array as do plutons from the Flagstaff Lake, Merrimack belt and the mafic rocks of the Meredith Porphyritic Granite. The appinites of Ach'Uaine (Fowler and Henney (1996) plot with the Wamsutta Diorite samples. (B) Ce/Nb versus Th/Nb diagram showing the distinct clusters of the Merrimack trough calc-alkaline rocks and the Nineteenmile Brook, Flagstaff Lake, and Meredith samples, suggesting origins in different arc systems.

Wamsutta Diorite–Similarities with Adakites

An unexpected result of this study is that the Wamsutta Diorite has compositions that indicate that adakite-like magmas were present in the Central Maine Trough at ~408 Ma. High Sr/Y values could result from plagioclase accumulation, but neither the modal amount of plagioclase nor the whole-rock Al_2O_3 contents (table 4) are high to suggest that the rocks are cumulates, nor are positive Eu anomalies present (fig. 8C). Likewise, the La/Yb values (fig. 10B) are adakite-like and this ratio is

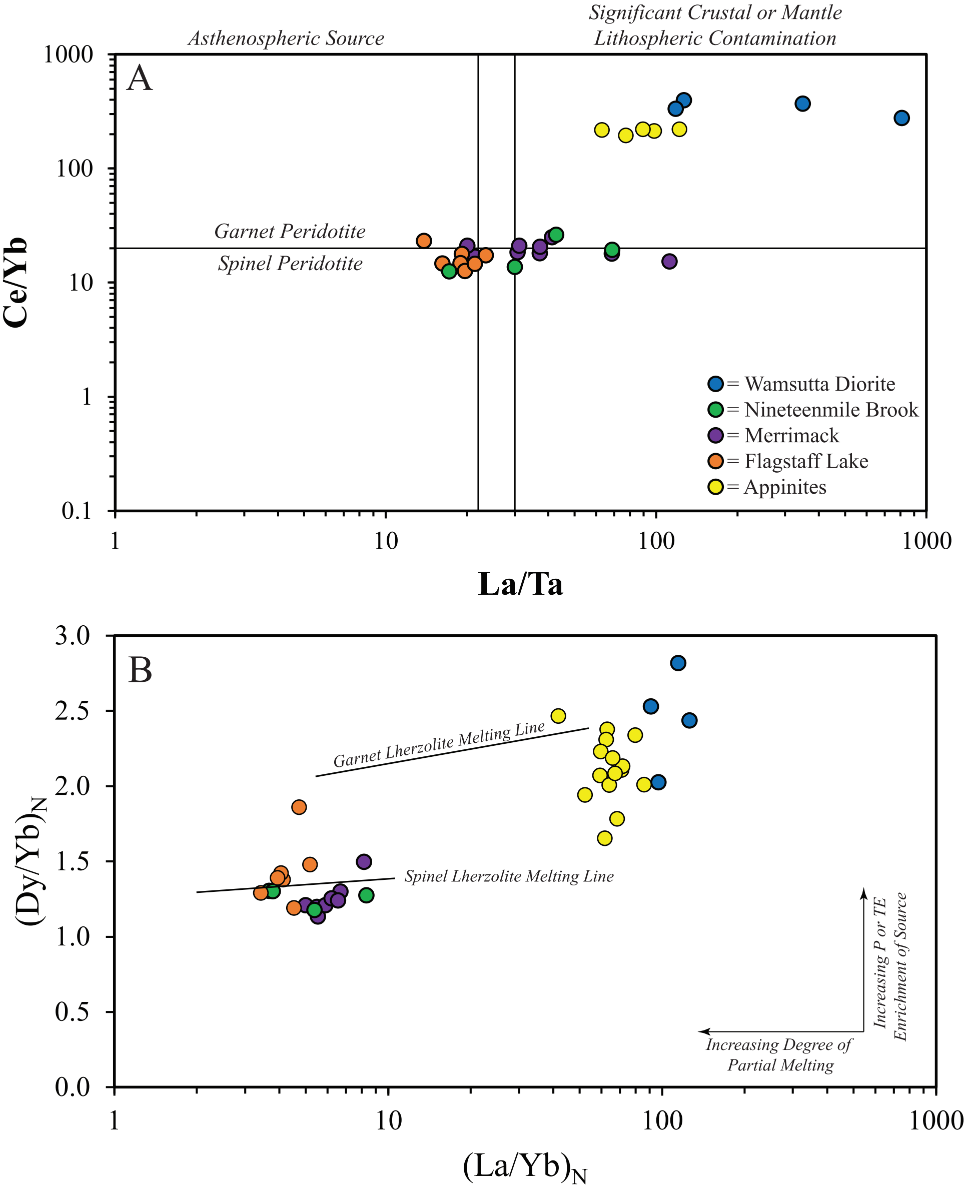

Fig. 14. (A) Ce/Yb versus La/Ta diagram (after Dorais and others, 2017) showing the Nineteenmile Brook, Flagstaff Lake, and Merrimack trough diorites plotting along the boundary between basalts with garnet and spinel peridotites ranging from asthenospheric to significant crustal or mantle lithospheric contamination. In contrast, the Wamsutta Diorite representing adakitic melts, and the Ach'Uaine appinites (Fowler and Henney, 1996), equilibrated with garnet peridotites at higher pressures. (B) $(Dy/Yb)_N$ versus $(La/Yb)_N$ diagram showing the Wamsutta Diorite and the Ach'Uaine appinites plot at high $(Dy/Yb)_N$ indicative of garnet lherzolite melting. In contrast, the Nineteenmile Brook, Flagstaff Lake, and Merrimack belt plutons plot along the spinel lherzolite melting line.

independent of plagioclase concentration. The spider diagram plots (fig. 9B) are also very similar to those of low silica adakites. Additionally, adakites are present elsewhere in the northern Appalachians (Wilson and others, 2005, 2017; van Staal and others,

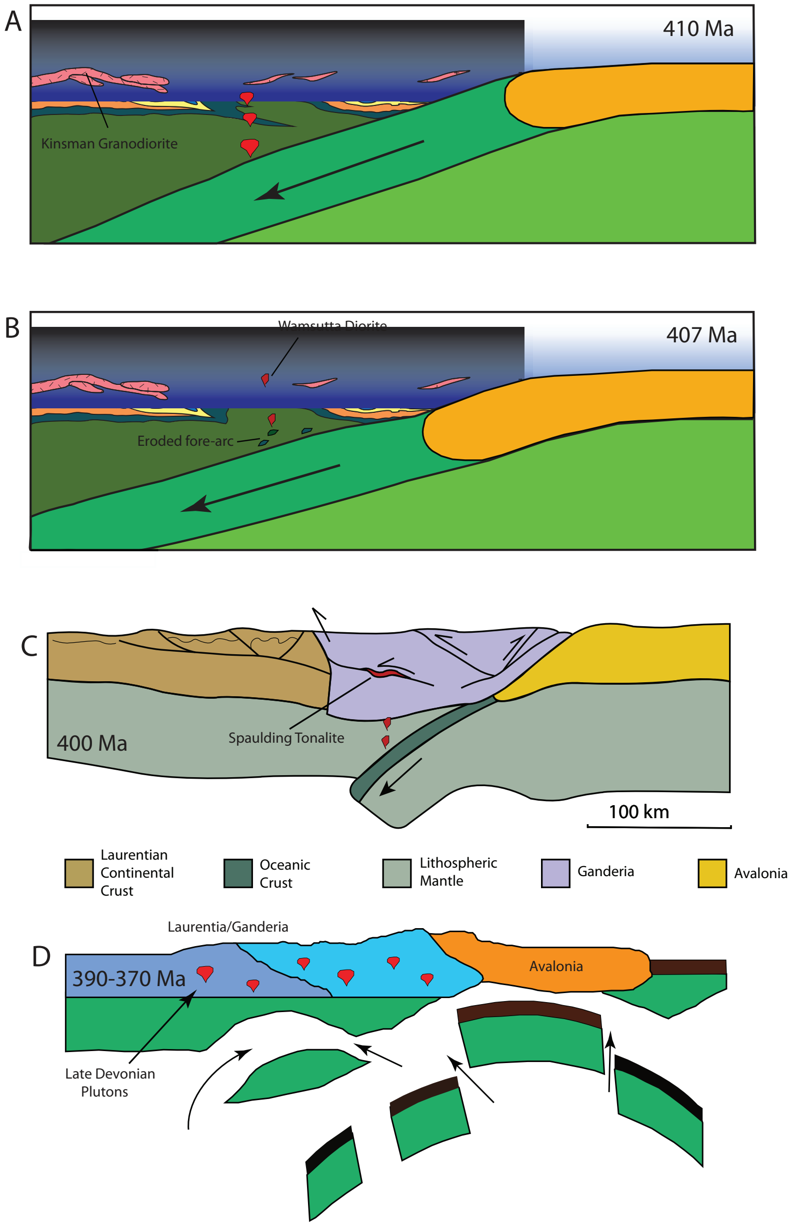

Fig. 15. Schematic diagrams illustrating the proposed tectonic settings that produced the magmas of the New Hampshire Plutonic Suite. (A) Between 413 and 410 Ma, arc magmas from the westerly dipping subducting slab were emplaced into the thickened overlying crust across central New Hampshire, providing the heat necessary for biotite dehydration melting, partially melting the metasediments to form the Bethlehem and Kinsman Granodiorites (After Eusden and Lyons, 1993). (B) At ~ 408 Ma, the Acadian deformational front migrated farther to the northwest and fragments of the eroded fore-arc that were distributed into the mantle wedge partially melted, producing adakitic magmas to form the Wamsutta Diorite (After Kay and others, 2005). (C) Continued westerly subduction produced arc basalts that, upon emplacement in the lower crust, caused amphibole dehydration melting to produce the Spaulding Tonalite (After Tremblay and Pinet, 2016). (D) Finally, lithospheric detachment allowed asthenospheric upwelling to partially melt the crust, causing post-tectonic anataxis and emplacement of mafic to felsic rocks of the Northeast Kingdom Batholith and the peraluminous Concord Granite of the NHPS (After Coish, 2010).

2009), indicating that the Wamsutta Diorite is not an anomaly. Hence, a review of ideas about the petrogenesis of adakites is appropriate (for example, Castillo, 2012).

Adakites were originally defined by Defant and Drummond (1990) as being partial melts of young, hot oceanic slab basalts and are characterized by SiO_2 contents of >56 wt.%, usually with MgO of < 3 wt.%, low Y and HREE, and high Sr concentrations, but with low high-field strength elements similar to those of island arc andesites, dacites and rhyolites. The high Sr/Y values and low HREE and Y are thought to result from partial melting of basaltic rocks at pressures higher than the plagioclase stability field with garnet sequestering the HREE and Y. Experimental work (Rapp and others, 1991; Rapp and Watson, 1995; Winther and Newton, 1991; Wolf and Wyllie, 1994; Sen and Dunn, 1994; Zamora, ms, 2000) indicates that vapor-absent melting of basalts at high pressures can indeed produce adakitic melts over a melting range of 10 to 40%.

Martin and Moyen (2003) and Champion and Smithies (2003) subsequently subdivided adakites into two groups based on SiO_2 contents: high SiO_2 adakites with silica contents >60 wt.%, and low SiO_2 adakites with silica values of <60 wt.%. The compositions of the high SiO_2 group match the experimental melts of basaltic rocks and are the typical adakites of Defant and Drummond (1990; fig. 7), but the low SiO_2 group does not match experimental melts because they have higher MgO contents (4–9 wt. %), higher Cr and Ni concentrations, and higher abundances of the less incompatible portions of the patterns displayed on spider diagrams from La to Yb (Martin and others, 2005; fig. 9B). It is thought that low SiO_2 magmas are produced by partial melting of delaminated basaltic rocks producing high SiO_2 adakitic melts from the sinking slab that subsequently interacted with overlying mantle peridotites during ascent, elevating the MgO, Ni, and Cr concentrations and lowering the SiO_2 contents of the melts compared to high SiO_2 adakites. The Wamsutta Diorite has SiO_2 contents similar to that of low SiO_2 adakites and also has spider diagram patterns (fig. 9B) from La to Lu are clearly a better match to low SiO_2 adakites, having higher concentrations of these elements than high SiO_2 adakites (Martin and others, 2005).

The Sr/Y and $(La/Yb)_N$ ratios of igneous rocks have been used to estimate crustal thickness in magmatic arcs (Chapman and others, 2015) and continental collision zones (Hu and others, 2017). These values were regressed against known crustal thickness for Quaternary to Miocene igneous rocks to derive equations relating Sr/Y and $(La/Yb)_N$ and depth. Using equations 1 and 2 from Hu and others (2017), the Wamsutta Diorite yields crustal thicknesses of 300 km and 99.6 km for Sr/Y and $(La/Yb)_N$ respectively, geologically unreasonable results. Hillenbrand and Williams (2021) recently calculated crustal thickness for this region of New England at ~400 Ma to be ~40 km. Note that the Sr/Y ratios of the Wamsutta Diorite are considerably higher than values of adakites published in the literature and of those used for crustal thickness regressions. A GEOROC search for adakites indicates that their Sr/Y ratios rarely exceed 200 (four anomalous samples in table 2 of Guo and others (2006) have Sr/Y ratios of >2000, but their figure 3 shows these rocks actually have Sr/Y of less than 80).

The Wamsutta Diorite is also anomalous compared to typical low SiO_2 adakites because it has lower Ni and Cr concentrations. Since partial melting of basaltic rocks cannot produce low SiO_2 adakites (Rapp and others, 1991; Rapp and Watson, 1995), I suggest that the first step in the petrogenesis of the Wamsutta Diorite was as a high SiO_2 adakitic melt at high pressures within the garnet stability field. This melt then interacted with peridotites to evolve to low SiO_2 adakites, but should initially have had higher MgO, Ni, and Cr contents than the Wamsutta Diorite. I infer that the magmas then fractionated olivine and pyroxene to lower the Ni and Cr concentrations respectively. If pyroxene was the dominant fractionating phase, the overall SiO_2 contents of the magma would not have significantly changed, accounting for the overall low SiO_2

values of the Wamsutta Diorite. Sr is incompatible in olivine and pyroxene and the fractionation of these minerals could have enriched its abundance to account for the anomalously high Sr concentrations and Sr/Y values of the Wamsutta Diorite. Such fractionation could also account for the unrealistic crustal thickness calculated via the Chapman and others (2015) and Hu and others (2017) methods. Some researchers have suggested that amphibole fractionation also contributes to the high Sr/Y values of adakites (Azizi and others, 2019; Xu and others, 2020).

Wamsutta Diorite–Similarities with Appinites

Appinites, hornblende-rich rocks that form small plutons associated in time and space with larger, batholitic granitic rocks (Bowes and Wright, 1967; Pitcher and Berger, 1972; Fowler and Henney, 1996), exhibit a wide range in compositions. As summarized by Murphy (2020), appinintes can develop in a multitude of environments if the mafic magmas are water rich. The geochemical variation is a function of the diversity of mantle source rock compositions. In general, they are broadly grouped as low K_2O, calc-alkaline appinites, and high K_2O, shoshonitic-like appinites (Murphy, 2013). In some cases, appinites have geochemical characteristics that are shared by adakites (Murphy 2020). The Wamsutta Diorite has textural characteristics that are reminiscent of appinites, hornblende comb layering and acicular and skeletal amphibole crystals are common in the pluton (fig. 2).

Chemically, the Wamsutta Diorite is more similar to the high K_2O appinites of Ach'Uaine, Scotland (Fowler and Henney, 1996); both have high LREE concentrations relative to HREE and Y (figs. 8C and 9C) that indicate derivation from garnet-bearing source rocks. The Ach'Unaine appinites are very U-rich with positive U anomalies on spider diagrams (fig. 9C. Some of these samples lack U analyses and the plotted U value is interpolated between Nb and K). The Wamsutta Diorite has a dominant, positive Sr anomaly that is not seen in the Ach'Uaine rocks, but the latter do have adakite-like Sr concentrations and $(La/Yb)_N$ values, and somewhat higher Sr/Y values than arc, calc-alkaline basalts (fig. 10).

In the Th/Yb versus Nb/Yb diagram (fig. 13A), the Scottish appinites and the Wamsutta Diorite rocks plot together at high values. Likewise in the Ce/Yb versus La/Ta and the $(Dy/Yb)_N$ versus $(La/Yb)_N$ diagrams (fig. 14) where the two cluster together. Both have ratios that indicate derivation from garnet peridotite sources.

The adakitic melts probably also interacted with highly metasomatized mantle that achieved high water contents from extensive slab dehydration. High water contents were imparted to the hybridized, low SiO_2 adakitic magmas that then achieved appinite-like amphibole textures from rapid crystallization during decompression (Murphy and others, 2012; Murphy, 2013).

Spaulding Tonalite

The next pulse of the New Hampshire Plutonic Suite is the Spaulding Tonalite that was emplaced ~400 Ma (Lyons and Livingston, 1977; Eusden and Barreiro, 1988). The metaluminous Spaulding Tonalite was originally named the Spaulding Quartz Diorite (Fowler-Billings, 1949), but subsequent work revealed that the major rock type of this NHPS member is tonalite, averaging 63% SiO_2 (Duke, ms, 1978; Dorais, 2003), and the name was changed to the Spaulding Tonalite (Lyons and others, 1997). Of the Spaulding Tonalite analyses found in Duke (ms, 1978) and Dorais (2003), 65% of the analyses have SiO_2 contents greater than 60 wt.% and only 10% have values less than 54 wt.%. The most mafic Winnipesaukee Tonalite rocks (46% SiO_2) with the most primitive isotopic values also have positive Eu anomalies, relatively sodic plagioclase ($<An_{44}$), and have amphibole compositions suggestive of crystallization from magmas with Mg#s of ~ 35 (Dorais, 2003, 2019a). Additionally,

plagioclase compositions in other plutons of the Spaulding Tonalite are oligoclase-andesine; no plagioclase more calcic than andesite has been reported in any Spaulding Tonalite pluton (Fowler-Billings, 1949; Greene 1970; Nielson, 1981). These mineral compositions indicate crystallization from magmas with intermediate compositions, not basalts. Hence, there is no evidence that the most SiO_2-poor rocks of Spaulding Tonalite represent mafic liquid compositions but rather, are cumulates.

The Winnipesaukee Tonalite, correlative with the Spaulding Tonalite, is isotopically more primitive than the average Bethlehem and Kinsman Granodiorites with $\varepsilon_{Nd\ (398\ Ma)}$ values between 0.1 and -5.4 and initial $^{87}Sr/^{86}Sr$ values between 0.7033 and 0.7066 (Dorais, 2003). The Winnipesaukee Tonalite also has a range of $\delta^{18}O$ values with some samples as low as 6.7, but the samples with higher silica values have $\delta^{18}O$ values between 9.6 and 10.5. The more primitive magmas could have differentiated from arc basalts. Recently, Tassara and others (2020) reported the discovery of Acadian hydrous ultramafic cumulate rocks of Connecticut formed by deep-seated ($\sim$1.1 GPa) fractional crystallization processes from mantle-derived parental melts. They proposed that these rocks represent the heretofore missing deep cumulate roots of the magmatic arc and concluded that differentiation of mantle-derived hydrous magmas by fractional crystallization and assimilation processes in the deep crust was a significant process in the petrogenesis of intermediate to silicic magmatism during the Acadian Orogeny. This model may be also applicable to the Spaulding Tonalite. However, as mentioned, the most mafic Spaulding samples are cumulates, and the rocks lack evidence of a compositional connection to arc parental magmas.

Spaulding Tonalite samples with higher initial $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values and lower $\varepsilon_{Nd\ (398\ Ma)}$ values indicate the Spaulding contains considerable amounts of continental crust, as do the depleted mantle ages range from 927 to 2809 Ma. Alternatively, rather than being differentiates of arc basalts, the originally defined I-type granitoid petrogenesis as originally espoused by Chappell and White (1974) may apply to the Spaulding Tonalite; the magmas were derived from partial melting of igneous rocks, probably amphibolites that were perhaps of Precambrian age from the basement complexes. Dehydration melting of amphibole requires temperatures in the range of 850 to 975 °C (Wyllie and Wolf, 1993; Wolf and Wyllie, 1994).

The origin of I-type granitic rocks as differentiates of more mafic magmas or as partial melts of amphibolites is still a subject of debate (Coleman and Glazner 1997; Ratajeski and others, 2001; Sisson and others, 2005; Clemens and others, 2011; Clemens and Stevens, 2012; Nelson and others, 2013; Jagoutz and Klein, 2018). Regardless of whether the Spaulding Tonalite magmas were direct partial melts of lower crust amphibolite or differentiates of mantle-derived parental magmas, its petrogenesis required an open system anatexis with heat and mass contributions from the mantle.

Synthesis of Tectonic Models

Figure 15 depicts my attempt to synthesis the available geochemical data for plutons of the New Hampshire Plutonic Suite with ages between 413 to 360 Ma to arrive at a more comprehensive model of magmatism associated with the Acadian Orogeny. This model combines those of Eusden and Lyons (1993), van Staal and others (2009), Coish (2010) and Tremblay and Pinet (2016). Panel A (after Eusden and Lyons, 1993) shows the setting across central New Hampshire following the collision of Avalonia with the Taconic and Salinic modified Laurentian margin (Bradley and others, 2000). Following collision, the Acadian deformation front migrated to the northwest across New England, deforming the sediments of the Central Maine trough, producing the dorsal structure of the metasediments of the Central Maine trough with both east and west verging thrusts. In central New Hampshire, the Bethlehem and Kinsman Granodiorites were emplaced as bases to the trust sheets during this stage of Acadian compression (~410 Ma; fig. 15A). The mafic rocks of the mingled zone in the Meredith Porphyritic Granite (a Kinsman member pluton) have calc-alkaline compositions that preserve mantle isotopic Nd and Sr values (Dorais, 2003). The Nineteenmile Brook pluton was probably emplaced at about this same time. Such rocks are not common in northern New England, and I infer that density filtering prohibited more of these magmas to reach higher crustal levels, or flat slab subduction limited magma production. Nonetheless, the high melting temperatures of the Kinsman Granodiorite (Dorais and others, 2009), attaining biotite dehydration melting, along with the mafic rocks of Meredeth Porphyritic Granite, indicate the input of both mantle heat and mass. At the same time, calc-alkaline plutons were emplaced in the Merrimack Trough of southeastern New Hampshire.

The similarity of the Wamsutta Diorite with low SiO_2 adakites requires that rocks with basaltic compositions partially melted and the melts then assimilated peridotitic rocks to attain their low silica contents (Martin and others, 2005). This model requires either 1) slab detachment and melting of these rocks at garnet stability pressures (Defant and Drummond, 1990); 2) delamination of mafic rocks from the lower crust and their partial melting in mantle peridotites (Gao and others, 2004; Wang and others, 2004, 2005); 3) differentiation of basaltic magmas at high pressures with garnet or amphibole fractionation generating the high Sr/Y values (Dehrer and others, 2005; Macpherson and others, 2006; Jagoutz and others, 2013; or 4) flat slab causing subduction erosion of mafic rocks that were mixed with the mantle wedge, partial melting, and the melts interacting with peridotites to obtain the low SiO_2 adakitic compositions (Kay and others, 2005).

The continuous migration of the Acadian Orogenic front across northern New England (Bradley and others, 2000) from ~423 to 382 Ma, a 40-million-year time span, suggests that slab breakoff did not occur between 413 and 400 Ma, the age range of the plutons considered here. Therefore, a partial melting origin of a detached slab appears not to be an explanation for these northern Appalachian adakites. Partial melting of delaminated mafic rocks from the lower crust can also generate adakites (Gao and others, 2004; Wang and others, 2004, 2005) as does high pressure differentiation of basaltic magmas in the garnet stability field (Dreher and others, 2005; Macpherson and others, 2006): neither process requires flat-slab subduction. However, several researchers have proposed flat-slab subduction occurred during this time period (Murphy and others, 1999; van Staal and others, 2009, 2012; van Staal and Barr, 2012; Wilson and others, 2017) as the slab flatted from rapid southerly motion of the composite Laurentian plate (van Staal and others, 1998). Paleomagnetic evidence (van Staal and others, 1998) shows that underthrusting of progressively more buoyant Avalonian continental crust was coeval with rapid southerly advance (*ca.* 7–10 cm/yr) of the Laurentian plate beginning at ~418 Ma (Whalen and others, 2006; van Staal and others, 2009, 2014), suggesting that this process may have led to swift overthrusting of the subducting hinge and hence flattening of the slab beneath composite Laurentia (fig. 15B, Murphy and others, 1999; van Staal and others, 2009, 2012, 2014).

As per van Staal and others (2009, 2012), evidence for flat-slab subduction includes: 1) the paucity of identifiable Paleozoic arc-trench gap rocks between the coastal arc and Avalonia. van Staal and others (2009, 2012) proposed that the fore-arc to the Acadian arc was largely tectonically removed, having been subducted beneath the leading edge of Laurentian-modified margin. This would require that the fore-arc rocks experienced considerable amounts of subduction erosion as the slab flattened; 2) the apparent migration of the structural front towards the back-arc region, for example, Acadian retro-arc fore-land deformation in northern New Brunswick; 3) the paucity of mafic rocks with subduction-zone geochemical signatures. Flat-slab subduction explains the scarcity or absence of Early Devonian or younger arc magmatism in the leading edge of the composite Laurentian upper plate; 4) adakitic-like rocks of this age are present in the Devonian felsic rocks of Gaspe, Quebec, New Brunswick, and Maine (Hon and others, 1992; Wilson and others, 2005; 2017; van Staal and others, 2009). These rocks have elevated La/Yb and Sr/Y ratios like adakitic volcanic rocks in Chile that have been associated with shallow subduction and/or subduction erosion (Kay and others, 1991, 2005; Haschke and others, 2002) where fragments of the fore-arc crust of the hanging wall were dragged down into the mantle (Kay and others 2005). I concur with Wilson and others (2005, 2017) and van Staal and others (2009) that the subduction erosion model for adakite generation best explains the composition of the Wamsutta Diorite and other adakitic rocks of the region.

Continued subduction (fig. 15C; after Tremblay and Pinet, 2016) placed basaltic magmas at the base of the crust, either differentiating and assimilating crustal rocks at depth to produce intermediate composition magmas or causing amphibole dehydration melting to form the metaluminous Spaulding Tonalite. These magmas were emplaced during the latest stages of Acadian tectonism in the moderately deforming Central Maine Trough metasediments; hence, they lack the strong deformation of the earlier emplaced Bethlehem Granodiorite (for example, fig. 18-4 of Dorais, 2019b).

The youngest member of the Hew Hampshire Plutonic Suite is the post tectonic, Concord Granite. These two mica granites, ranging in age from 390 to 360 Ma, were emplaced across northern New England. Thermal modeling predicts that lower crustal rocks partially melt 30 to 50 m.y. after crustal thickening because of the delay of high temperature isotherms to sweep upward through the colder, depressed crust (England and Thompson, 1984; Chamberlain and England, 1985; Zen, 1988). This model, plus the contribution of thermal energy generated by the U- and Th-rich sediments (Chamberlain and Sonder, 1990), can explain the presence and age of the two-mica Concord Granites. However, several of the 370 to 390 Ma plutons of the Northeast Kingdom Batholith of Vermont (Ayuso and Arth, 1985; 1992; Arth and Ayuso, 1997), portions of the 377±2 Ma Mooselookmeguntic Pluton of Maine (Tian, ms, 2000; Centorbi, ms, 2002), and the 383.8±2.2 Ma garnet tonalites of the Flagstaff Lake Igneous Complex of western Maine (Gibson and others, 2021; Nielson and others, 1989), all of the same age range of the Concord Granites, include gabbros and diorites, rocks that are too mafic to have been produced by the thermal relaxing melting models resulting from crustal thickening. These mafic rocks indicate that there had to have been mantle mass and heat contributed to the crust during this 390 to 370 Ma time period.

Coish (2010) reviewed the petrogenesis of the Northeast Kingdom Batholith of northeastern Vermont. He noted that these rocks have trace element compositions suggesting of a volcanic arc setting but suggests that the timing of their emplacement was long after subduction ceased. Coish interprets these plutons as resulting from detachment of either the subducted slab or of a thickened lithosphere that was produced during the Acadian collision (fig. 15D). Asthenospheric upwelling heated the lower crust to generate arc-like magmas whose compositions resulted from melting of rocks previously produced in the subduction zone system and are not direct products of subduction which had ceased by this time.

The effects of lower crust detachment and an asthenospheric upwelling event at ~390 Ma could have impacted a relatively large area, causing partial melting and plutonism over a widespread region. Plutons with ages between 370 and 390 Ma are not limited to the mafic rocks of northeastern Vermont and western Maine but include the peraluminous Concord Granites that were emplaced across eastern Vermont, New Hampshire, and western Maine (Osberg and others, 1985; Lyons and others, 1997;

Ratcliffe and others, 2011). While crustal overthickening can produce temperatures for the Concord Granite anatectic event that caused muscovite dehydration melting (England and Thompson, 1984), these temperatures are not sufficiently high to produce the mafic rocks emplaced during this time span (Jamieson and others, 1998; Roselle and others, 2002; Lyubetskaya and Ague, 2010). Ambient heat from mafic magmas could have contributed to widespread crustal temperatures exceeding muscovite dehydration and the genesis of the Concord Granite.

Finally, outboard of all these Central Maine and Connecticut Valley-Gaspe belt plutons is the peri-Gondwanan Merrimack belt (Wintsch and others, 2007; Hussey and others, 2010). The Exeter Diorite of the Merrimack belt has been dated at 407 Ma (Bothner and others, 2009), the same age as the Wamsutta Diorite. The Sweepstakes and Dracut diorites have not been dated, but their subduction zone signatures complement the evidence provided by the Exeter Diorite. Instead, it is possible that these arc magmas were generated in a different, easterly dipping subduction zone, the Coastal Volcanic Arc, in the Merribuckfred trough in the Rheac Ocean (Hussey and others, 2010). The separate clustering of the Nineteenmile Brook, Flagstaff Lake, and the mafic rocks of the Meredith Granite from the Merrimack trough plutons in figure 13B permits this interpretation. Plots of ratios of highly incompatible elements such as Ce/Nb versus Th/Nb are useful because the ratios do not vary during crystal fractionation or batch partial melting. The slopes of correlation lines on this type of diagram gives the ratios of the concentrations of the elements in the source rocks. In this diagram, the Nineteenmile Brook, Flagstaff Lake, the mafic rocks of the Meredith Granite have an average Th/Ce ratio of 0.06, slightly lower than the 0.12 average for the Merrimack trough plutons, not a distinctly different ratio that would prove different mantle sources from different subduction zones. But the Merrimack rocks plot separately from the Central Maine trough plutons at considerably higher Th/Nb and Ce/Nb values. Basalts from the same subduction zone tend to show less range in these ratios (Saunders and Tarney, 1991; Béziat and others, 2000; Khanna and others, 2017), and the extensive range in ratios between the cluster of the Central Maine trough plutons and the Merrimack trough plutons can be interpreted as evidence for separate subduction zones for each group. Hence, a Mollucan-style closure of the Iapetus Ocean (Bradley, 1983) is permissible to explain the closure of oceanic tracts during the Paleozoic.

An alternative explanation for the two distinct clusters displayed in figure 13B is that the Nineteenmile Brook, Flagstaff Lake, and mafic rocks of the Meredith Granite plot very near the field for back-arc basalts. A mixed arc and within-plate compositional signature have long been recognized for the Silurian – Early Devonian Piscataquis belt (Hon and others, 1992). Such a signature could reflect a back-arc setting where the strength of the arc component signature depends on the degree of subduction zone fluid enrichment of the mantle wedge. In this scenario, the Nineteenmile Brook, Flagstaff Lake, and mafic rocks of Meredith Granite could represent more of a back-arc setting and the Merrimack trough plutons representing the arc itself. Both magma types could have been generated in a westerly dipping subduction zone, negating the need of a Mollucan-style model.

CONCLUSIONS

The Nineteenmile Brook Diorite shares calc-alkaline compositions with the ~410 Ma mingled rocks of the Meredith Porphyritic Granite and the arc rocks of the Merrimack trough of southeastern New Hampshire. While not yet dated, this similarity in compositions indicates that the Nineteenmile Brook Diorite is also a product of subduction zone magmatism. Its position, inboard of the modified Laurentian margin, is indicative of a western polarity for the subduction zone, especially because the pluton was emplaced in the Central Maine trough that was adjacent to Laurentia at that time. Underplating of these arc magmas provided heat for crustal anataxis, forming the high temperature, peraluminous Kinsman Granodiorite magmas of the NHPS. Portions of these arc magmas are present in mingled zones in the Kinsman Granodiorite member of the suite.

Shortly thereafter at ~408 Ma, the Wamsutta Diorite was also emplaced in the Central Maine trough. The diorite has low SiO_2 adakitic compositions, suggestive of partial melting of basaltic rocks within the garnet stability field, producing the high La/Yb and Sr/Y adakite signatures. I suggest that this partial melting event occurred after subduction erosion removed portions of the fore-arc to the mantle wedge. Here, these basaltic rocks partially melted to produce high SiO_2 adakitic magmas that subsequently interacted with the surrounding peridotitic mantle during ascent to evolve to low SiO_2 adakites. Continued westerly subduction added mafic magmas to the base of the crust and partially melted amphibolites to generate the metaluminous ~400 Ma Spaulding Tonalite.

Finally, lower crustal delamination at ~390 to 380 Ma, permitted mantle upwelling to partially melt lower crustal mafic rocks to produce the more mafic rocks of the Northeast Kingdom Batholith, Vermont, the mafic rocks of the Mooselookmeguntic Pluton, and the garnet tonalites of the Flagstaff Lake Igneous Complex of Maine. This same heat source could have contributed to the widespread melting event that generated the Concord Granites that were emplaced across Vermont, New Hampshire, and western Maine.

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